CAPACITY AND LEVEL OF SERVICE ANALYSIS OF BIDIRECTIONAL SINGLE LANE ROADS IN LEVEL TERRAIN

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Dedicated to
My beloved Parents

CERTIFICATE

This is to certify that the work contained in this thesis entitled *"Capacity and Level of Service Analysis for Bidirectional Single Lane Roads in Level Terrain"*, submitted by C. Ramesh in partial fulfillment of the requirements for the award of Master of Technology is a bonafide record of research carried under my supervision and guidance and that this work has not been submitted elsewhere for the award of a degree.

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ABSTRACT

The main objective of the present work is to determine the capacity and to describe the level-of-service on an ideal, bidirectional single lane road using the Indo Swedish Traffic Simulation model.

The problem is essentially carried out in two stages.

In the first stage, passenger car equivalents (PCE) of truck, bus, and tractor are calibrated using a new concept called vehicle throughput. The vehicle throughput of a traffic stream represents the number of vehicle kilometers, the stream has actually traveled in a unit interval of time. Two methods of calculating passenger car equivalents are proposed. The first method uses the number of cars displaced by the vehicle under investigation for determining passenger car equivalents while the second method uses the reduction in throughput caused by introducing the vehicle into an ideal traffic stream, i.e, an all Maruti Car stream, as the basis for determining the same. The PCE of a vehicle is treated as a quantity varying dynamically with flow, composition, etc.,

In the second stage the capacity of a single lane road is determined by studying speed-throughput-flow relationship of the ideal traffic stream under ideal road conditions. The capacity of a road is defined as the flow corresponding to the maximum throughput achievable. The level-of-service is determined using speed and density as criteria. The effect of each incremental addition of truck, bus and tractor in the ideal stream on the speed-throughput relationships is investigated. The various available levels of service for these traffic conditions are determined using speed as the criteria. Finally a heterogeneous traffic stream is simulated to represent the practical situation and to show the effect of congestion.

CHAPTER 1

INTRODUCTION

1.1 General

Road transport plays a significant role in India's transportation system and is a vital sector in the country's economy. During last four decades, road transport has rapidly gained importance in overall transport system of the country. The total number of all types of mechanized motor vehicles increased from a mere 3 lakhs in 1950–51 to 192 lakhs in 1989–90 [8]. This can be attributed to the fact that road transport has certain inherent advantages like door to door service etc., With traffic on Highways increasing, the demand for upgrading the roads from their existing status has exerted substantial pressure on planners. In order to select most beneficial scheme from among a number of proposals, it is necessary to have an economic appraisal of various alternatives. Rational decisions will be required before undertaking such improvements. This necessitates the availability of reliable information regarding capacity and operational conditions of the proposed or existing facilities.

1.2 The Road and Traffic Scenario in India

Indian roads compose primarily of single lane, two lane and four lane undivided and divided carriage ways. A very few amount of the roads have six lanes and eight lanes with divided carriage ways. In rural areas single lane roads which have a pavement width of about 3.75m are predominant. The roads with pavement of 5.5m wide are known as intermediate lane roads and that of 7m wide are the two lane Highways. The four lane divided carriage way roads are 14m to 15m in width, and are provided with a median barrier. In general all the roads are provided with earthen

shoulders on either side. Some times part of the shoulders of the single lane roads have been improved with brick paving to increase the effective width of the roads to facilitate the ease of movement of the vehicles. The brick paving varies in width from about 0.5m to 1.6m. These shoulders play a very important role during crossing and passing maneuvers. According to the updated Road User Cost Study (RUCS), good paved shoulders can increase the capacity of the road by about 20 to 30 percent. Realizing the need for good shoulders, the Indian Roads Congress (IRC) recommends that good quality shoulders such as moorum shoulders be provided, on all types of roads.

The road traffic on Indian roads is highly heterogeneous, being constituted by vehicle types as fast as Maruti Cars and as slow as bullock carts. It has been estimated that there are about 15 million bullock carts in the country today, carrying significant volumes in areas not even linked by all–weather roads. The fast moving vehicles include light commercial vehicles, cars, trucks, buses and several other categories of two wheelers. Among the slow moving vehicles, bicycles, cyclerickshaws and animal drawn vehicles dominate the scene.

1.3 Need for Capacity Analysis of Indian Roads

One of the main reasons for growth of congestion on Indian Highways is that the growth of traffic has outpaced the growth of Highway network. The total length of National Highways increased only by about 70 % between 1950–51 and 1989–90 while the increase in all other roads (State Highways, District roads and Village roads etc.,) is of the order of 544 %. Also in 1950–51, only 39 % of total road length was surfaced. This rose to 43.3 % in 1970–71 and 46.7 % in 1984–85 respectively. The latest available information does not indicate any significant increase

in the proportion of surfaced roads. If we compare the above mentioned percentages with the percentage increase in growth of mechanized motor vehicles during the same period (which is an indicator of growth of traffic), which is of the order of 6300 % (see section 1.1), the increase in road congestion gets answered and the need to upgrade the road network gets reinforced.

Information regarding the capacity and level-of-service on an existing road is very important for upgrading that road. Unlike the western countries where extensive research has been done in this field and where procedures for capacity analysis exist for each and every type of Highway facility, comparatively little work has been done in this field in India. Except for the guide lines for capacity analysis on urban and rural roads, which the IRC publishes from time to time, the transportation planner in India has little to choose from. No methodologies have been prescribed for the capacity analysis of Indian roads and the existing guide lines are based solely on the speed–flow relationships established during the initial [3] and updated [4] versions of RUCS. The very fact that only two parameters i.e., the speed and flow , have been the basis for determining capacities right from single lane roads to four lane divided carriage ways, prompts for extensive studies on capacity analysis of Indian roads.

1.4 Role of Simulation in Traffic Engineering

The complexity of modern traffic system management strategies often require that predictive modeling studies be conducted prior to the implementation of any strategy. Two basic approaches used for traffic modeling are analytical and simulation. Analytical models attempt to obtain solution by means of a single equation, or a limited number of equations. Thus their use is confined to simple traffic engineering problems. Simulation models on the other hand attempt to find solution by

means of sequential and iterative application of equations and inequalities. Therefore, their applications are extended normally to the complex situations of traffic systems where a large number of variables and constraints play significant role.

Simulation has been recognized since long as a powerful problem solving technique. Apart from the advantage cited above the following facts also favour simulation of traffic operations:

- Simulation of complex traffic operations may provide an indication of which variable is important and how they relate. This may later lead to successful analytical formulation.
- Simulation is cheaper than many forms of experiment. It offers the opportunity for the investigator to collect as much data as is needed for the meaningful inference to be drawn from the results. This reduces the difficulties of collecting huge amounts of field data.
- Simulation gives an intuitive feeling for traffic system being studied and is therefore instructive.

Thus we can say that a properly modeled and thoroughly validated simulation model can represent realistically highly complex traffic systems. Hence the present work focuses on the application of the Indo Swedish Traffic Simulation Model for the capacity analysis of single lane roads.

1.5 Statement of the Problem

Keeping in view the need for capacity analysis and the universal shortage of data, for narrow roads, as explained above, it was decided that speed–flow relationships for single lane roads be studied first for ideal road and traffic conditions, and then the effect of each incremental addition of truck, bus and tractor on the speed–flow relationships be investigated using the Indo Swedish Traffic Simulation Model.

A prerequisite for developing speed–flow relationships for mixed traffic conditions is the need to express the relative effect of all types of vehicles in terms of a standard vehicle, which is usually a passenger car. Hence Passenger Car Equivalents (referred to as PCE hereafter) are to be calibrated for the type of vehicles which will be used in the study. Once PCEs are calibrated the next step is to develop speed–flow relationships for mixed traffic. The capacity of single lane roads is to be determined using the concept of vehicle throughput.

1.6 Organization of the Thesis

The thesis is presented in five chapters. Chapter 2 presents the detailed description of Indo Swedish Traffic Simulation Model, the traffic submodel and the road submodel.

Chapter 3 introduces the concept of vehicle throughput and the computation of PCEs of truck, bus and tractor using the same. The effect of each incremental addition of truck, bus and tractor on the acceleration noise of the stream is also studied.

Chapter 4 presents the development of speed–throughput-density relationships on single lane roads for ideal conditions and the calibration of level-of-service for the same.

Chapter 5 presents the summary of the present work, conclusions drawn from the study and the possible extensions are also suggested.

CHAPTER 2

INDO SWEDISH TRAFFIC SIMULATION MODEL

2.1 History

A stochastic discrete event simulation model was developed by the Swedish National Road and Traffic Research Institue for the two lane bidirectional traffic system during the period 1965-1977 [2]. It has a long history of calibration and validation over a number of road stretches in Sweden. Subsequently the model has been used for traffic analysis in providing auxiliary lanes in Finland and the United Kingdom. While RUCS was initiated in India, the need to develop a simulation model for the Indian road and traffic conditions was felt. Accordingly, an evaluation of several models existing before 1980 led to the conclusion that the best available and reliable model was the one developed by the VTI. This model was formed the basis for work done in subsequent years at the Indian Institute Of Technology, Kanpur in collaboration with the scientists of VTI. The version of the model is currently known as the Indo Swedish Traffic Simulation Model.

2.2 Description of Indo Swedish Traffic Simulation Model

The traffic and road conditions prevailing in India are too complex to model by simple approaches. It is necessary to incorporate the heterogeneity of traffic and the hosts of road widths along with shoulders. The basic structure of the VTI model was such that it had built in features that allowed the restructuring the of the model for Indian conditions (Gynnerstedt,1983). The program and the data structures are based on the Jackson Structured Programming (JSP) technique and has been programmed in one of the highest level simulation languages - SIMULA 67. Simula

has built in features like pseudo-parallel execution that facilitates simulation of any process. The model has been calibrated and validated extensively for single, intermediate and two lane roads in India.

2.2.1 General Program Design

The program mainly consists of two processes, which also contain the data and procedures. They are

1. Process class generator process
2. Process class vehicle

The vehicle generator process creates the road objects and allots the individual driver vehicle attributes. Here they are also allotted their traffic attributes. Parameters which define the vehicles are identity number, basic desired speed and power mass ratio. Parameters giving their traffic attributes are origin of the vehicle, destination of the vehicle and entry time. The vehicle generator process also activates vehicles at their starting times.

The vehicle process describes all possibilities for action that a particular vehicle can have, for example ' *drive as freely moving vehicle* ', ' *follow another vehicle* ', ' *overtake the vehicle in front* ' ' *change to another track* ', etc., The freedom of choice covers mainly the set of alternatives that any vehicle can have and the actions are assumed to occur at momentarily calculated times. At each event the model data concerned is updated and a particular event is generated from among the possible event types. A note of the predicted event is inserted chronologically and logically in a two way linked list and the events are executed in this order.

The ordinary cycle for any arbitrary vehicle is

1. Predict the time of next event -- PREDICTNEXTEVTIME

2. Wait for the predicted time -- HOLD

3. Move the vehicle in time and space -- DRIVE

During the phase one of the cycle the next event time, the time of passage of next block border, the speed from the preceding event to the next event and the predicted speed for the passage of next block border are calculated in the procedures, PREDICTNEXTEVTIME, PREDICTBLBORDERTIME, AVERSP and PREDICTBLBORDERSP. During phase three of the cycle the procedure DRIVE updates the attributes LOCALTIME (*time of preceding event),* LOCALCOORD (*Road coordinate at preceding event),* AVERSP, PREDBLBORDERTIME, PREDICTBLBORDERSP.

During phase three of the cycle it may so happen that an adjacent vehicle or an oncoming vehicle interacts with the current vehicle with the result the predicted time of the next event for this vehicle is shown incorrect as it will occur earlier. Thus, its ordinary cycle is interrupted and the current vehicle considers that a surprise has occurred through the procedure SURPRISE. The prediction of the new event time for a vehicle is then made.

2.3 Program System

The various subsystems of the entire program system and their linkages are represented in the Fig 2.1. Simulation program is the heart of the system.

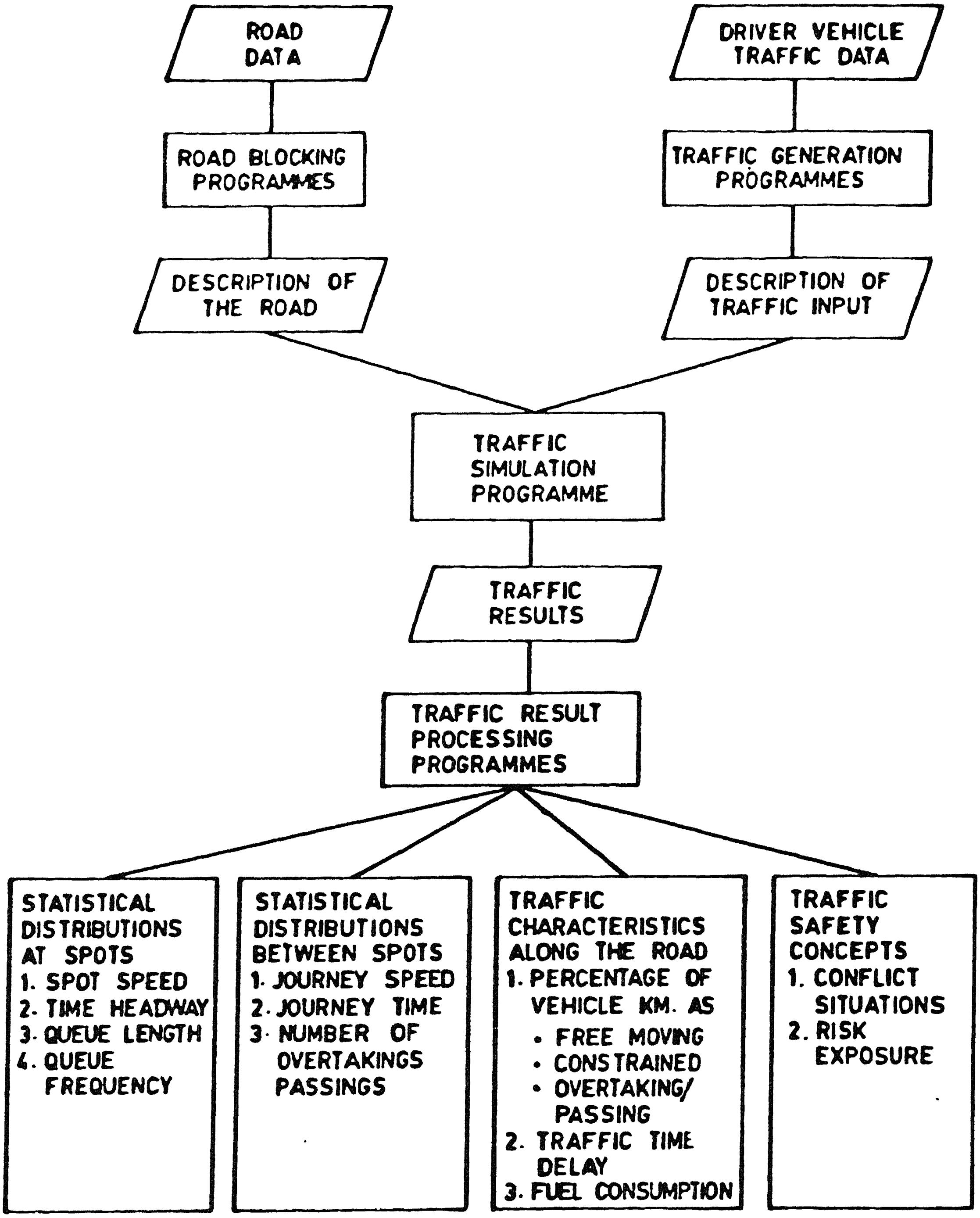

FIG. 2.1 PROGRAMME SYSTEM FOR TRAFFIC SIMULATION

2.3.1 Road Blocking Program

This program generates the road description as needed for the simulation program. Using the road geometry and traffic regulation data, the road is divided into homogeneous blocks. The minimum and maximum length of a block can be specified by the user. The sight distance break points are also calculated in this program.

2.3.1.1 Track or Lane Classification

The model divides the road width into the following three tracks or lanes in each direction of travel as shown in the Fig 2.2.

```
                 ---------------------------------------------
        Lane 3 ----->
                 _____________________________________________

Direction of travel ---->
         Lane 2 ---->                          <---- Lane 1
                 _____________________________________________

                                               <--- Direction of travel
        Lane 1 --->                            <---- Lane 2
                 _____________________________________________

                                               <----- Lane 3
                 ---------------------------------------------
```

Fig 2.2 Classification of Tracks or Lanes in the Model

Lane No.1: The wrong lane of travel *(A overtaking vehicle occupies this track during lane change in overtaking operations)*

Lane No.2: The usual lane of travel of a vehicle

Lane No.3: Represents shoulders or extra lanes (*This lane is used by the vehicle when yielding to a faster vehicle from behind and during crossing impedance*)

2.3.2 Traffic Generation Program

This subsystem generates the traffic for the simulation model. Traffic input for each vehicle is given in the form of vehicle identification, entry time in road stretch, direction of travel, entry speed, basic desired speed and power weight ratio. This input is derived either from the observed traffic data or through this traffic generation program .

Generation program uses the parameters like

- Total flow
- Flow changes
- Flow in each direction
- Traffic composition

2.3.3 Traffic Simulation Program

This is the heart of the entire system. It inputs the road description and traffic description as obtained from the first two subsystems. The road is divided into homogeneous sections termed as "*block*" with respect to road width, speed limit, horizontal curvature, gradient and overtaking restrictions. A change in any of these factors marks the beginning of a new block.

Vehicles interact with each other as they move over the road sections. A vehicle is said to be interacting with surrounding vehicles when its behavior is affected by another vehicle or group of vehicles. Interaction of vehicles in traffic with each other constrains them to move at the desired speed of each vehicle type.

The simulation process is based on event scanning system. The events are scanned in chronological order and at each new event, the model data concerned is updated. The status of the vehicle is updated at the end of every event

2.3.4 Traffic Results Processing Program

The traffic results obtained from the simulation model are analyzed in this sub system to obtain

- Statistical distributions of various measures of effectiveness that can be used for validation and sensitivity analysis
- Description of traffic along the road which can be used for determining many of the traffic parameters like acceleration noise, density etc.,

2.4 Indo Swedish Road Submodel

The logic adopted here is that the traffic is prevented from maintaining its basic desired speed by the following factors

- Road width less than 12 m.

Here it is assumed that the roads over 7m width are built with carriage way and the remaining width consists of two hard shoulders. For road width under 12m, the median basic desired speed, V_{0m}, is reduced to median speed V_{1m}.

- Curves with radius less than 1000m.

The curves with radius more than 1000 m do not effect the median speed V_{1m}. If, however the radius is less than 1000 m, the median speed, V_{1m}, is further reduced to V_{2m}.

- Effect of surface roughness

In the presence of surface roughness the median speed V_{2m} is further reduced to V_{3m}.

For each vehicle the speed is determined based on the first three factors and the effect of gradient is then superimposed to obtain the free speed. After the median speed V_{3m} is calculated the resulting distribution of V_{3m} is calculated using a transformation measure as explained in the next section.

2.4.1 The Transformation Measure

The transformation measure Q indicates how far the basic desired speed must be rotated about the median speed V_{3m} for free speeds. Thus, Q value is function of median speeds V_{0m}, V_{1m}, V_{2m}, V_{3m}. The free speed distribution V_{3m}, is determined using Q value transformation as follows

$$V_{0i}^{\,Q} - V_{3i}^{\,Q} = V_{0m}^{\,Q} - V_{3m}^{\,Q}$$

where V_{0i} and V_{3i} are speeds at arbitrary percentile i in basic desired speed and free speed distributions.

If Q value is equal to one the above equation results in purely parallel shift indicating a constant reduction in speed for fast as well as slow moving vehicles.

However when Q value is less than one the free speed distribution V_{3m} is rotated to anti clock wise direction showing that a driver with a higher BDS reduces his speed more than a driver with a lower BDS when influenced by speed reduction factors. It must be noted that smaller the value of Q the larger will be the rotation indicating that the driver with higher BDS reduces his speed drastically due to speed reduction factors than the driver with low BDS.

2.5 The Indo Swedish Traffic Sub model

This model assigns the vehicle characteristics as well as traffic characteristics (Starting point, starting time and destination). This model was originally developed by Clive Gilliams of Mathematical Advisory Unit of the U. K department of Transport. The distributions of the vehicles among the various classes, i.e., cars, trucks, scooters etc., is to be specified in the input data. Some of the procedures for generating the vehicles and traffic parameters are explained below.

Identification number: This is trivially generated by incrementing each time a vehicle is generated to enter a simulated road stretch at the specified coordinate.

Vehicle type: The vehicle type of individual vehicle is obtained from the distributions specified for the anticipated traffic composition.

Basic desired speed: The vehicles are uniformly distributed over the basic desired speed distribution for each vehicle type as specified in the input.

Power to mass ratio: The power equation is obtained by the considering the various forces acting on the vehicle such as the air resistance , rolling resistance, the gravitational force induced due to gradient and the tractive force at the wheels.

Entry time: The entry time for each vehicle entering the simulated road stretch is generated using the Shchul's (1955) composite time headway model.

The usual form of the composite distribution is

$f(t) = (1-\alpha) * g(t) + \alpha * h(t)$

Where

f(t) is the probability density function of the composite headway distribution.

g(t) is the density function for headway distribution of free moving vehicle.

h(t) is the probability density function for constrained vehicles.

α is the proportion of constrained vehicles.

Entry speed: This is taken as follows.

$0.85 * BDS$ if vehicle is free

$0.85 * (BDS)_{minpl}$ if vehicle is constrained, where $(BDS)_{minpl}$ is the minimum BDS among a platoon of vehicles.

However, these speeds are constantly reassessed once the vehicle enters the road stretch to be simulated. Hence the entry speeds assigned are comparatively less important.

2.6 Interactions on Narrow Roads as Dealt by the Simulation Model

2.6.1 Passing Maneuver

The restrictions of road width imposed by narrow roads tend to inhibit and limit overtaking interactions, as far as overtaking is concerned. Hence in the simulation model it is assumed that no overtaking is possible on single and intermediate lane roads. A faster vehicle can only pass a slower moving vehicle if the later yields space and moves partly to the shoulders. Thus the passing maneuver is due to the following two factors:

- The restriction of road width due to which a faster vehicle cannot actually move to a wrong lane to pass the slow moving vehicle.
- The inclination of the driver of the leading vehicle to yield space that is a random variable.

The Fig 2.3 describes the passing maneuver as performed in the simulation program.

The simulation program assumes that a slow moving vehicle yields space and moves to shoulders with a certain probability called *'lane3 probability'*. The following values of *'lane3 probability'* are adopted for this work.

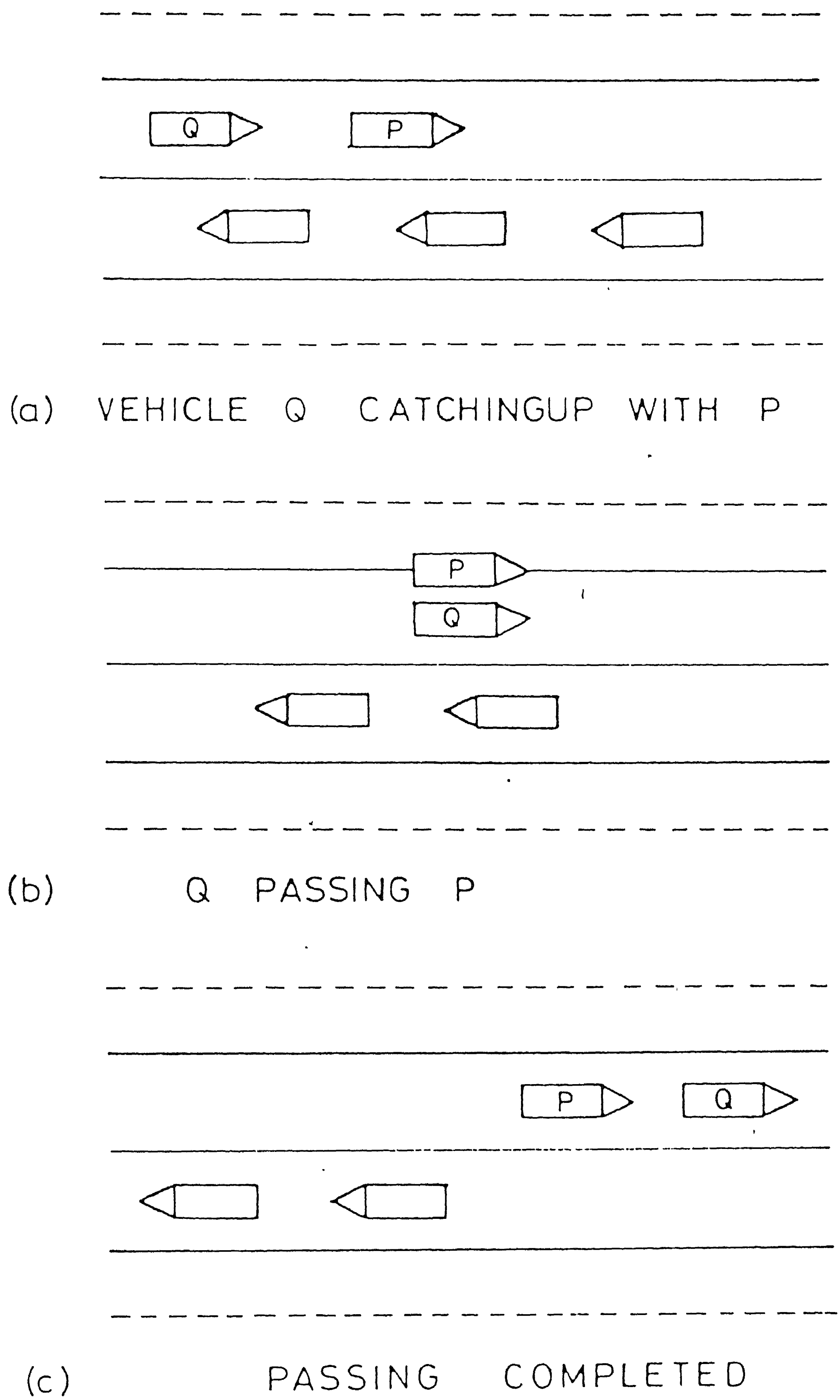

FIG. 2.3 PASSING MANOEUVRE DESCRIBED IN INDO-SWEDISH TRAFFIC SIMULATION MODELS

Flow in either directon (Veh/Hr)	lane3 probability (For all vehicle types)
< 51	1.00
51 < Flow < 101	0.80
101 < Flow < 151	0.50
151< Flow < 201	0.30
> 201	0.10

The passing maneuver as considered as by the model can be explained through Fig 2.3.

2.6.2 The Crossing Maneuver

So far as the meeting and crossing interactions are considered, they are not only unavoidable but also involve greater degree of interaction which increases with the reduction in road width. The degree of interaction involved is explained through Fig 2. 4 which shows speed profile of two vehicles crossing each other.

2.6.3 The Transformation Measure for Crossing Speeds

As mentioned in section 2.4.1 the basic desired speed is reduced to median speed V_{3m} when influenced by road width, horizontal curvature and surface roughness. This median speed V_{3m} is further reduced to V_{3m} under the influence of crossing impedance. The transformation measure for crossing speeds, CQ value, is an index which shows the trend in the reduction of speeds during crossing maneuvers for vehicles moving at a higher BDS to that moving at lower BDS.

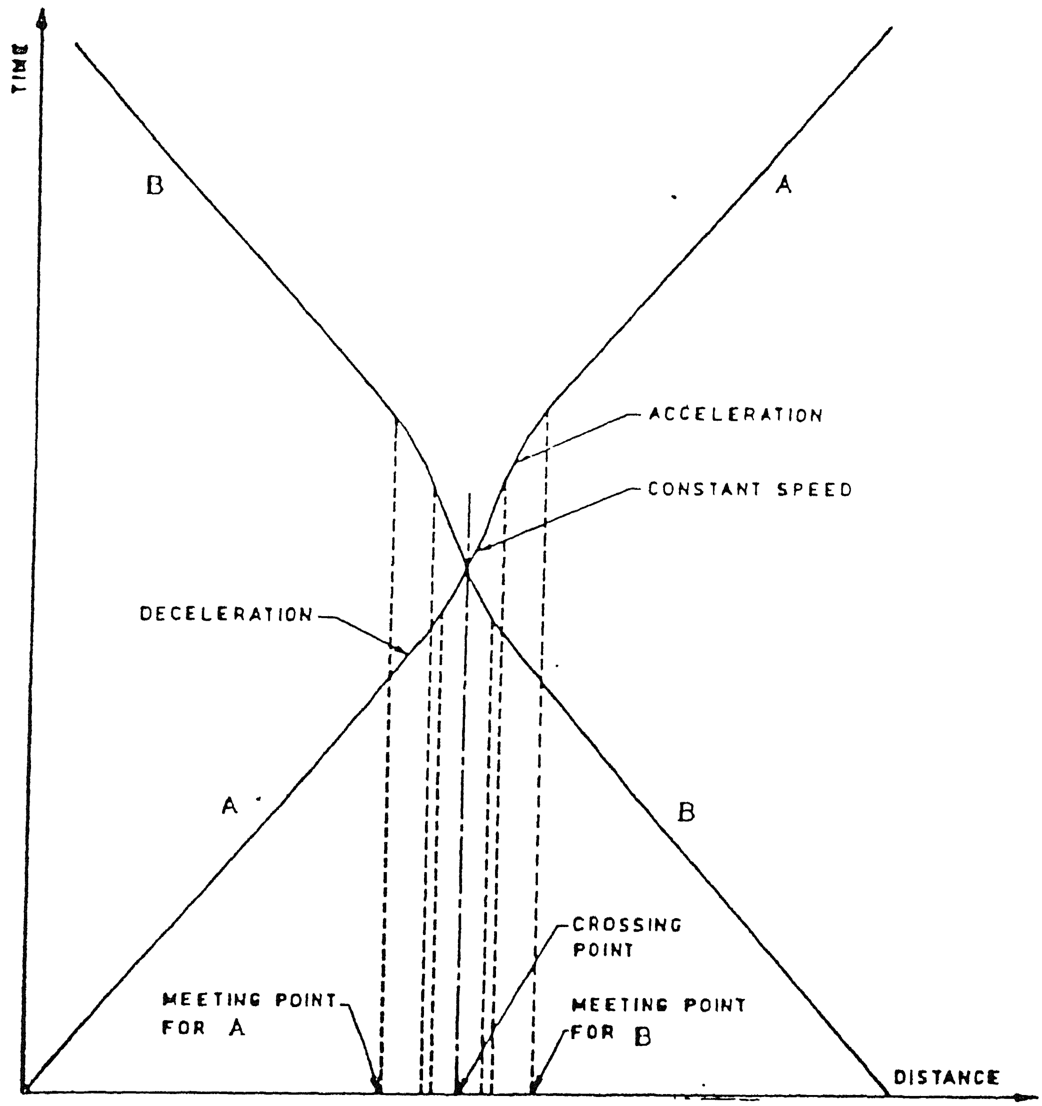

FIG. 2.4 TWO VEHICLES MOVING WITH THE SAME SPEED IN CROSSING SITUATION

In the main simulation for all vehicle types in every road block, the free block cross speed is calculated using the following equation

$$\text{Free block cross speed} = (VON^{CQ} + CVQ)^{1/CQ}$$

Where VON is the basic desired speed. This basic desired speed is obtained from the BDS distribution of the vehicle from traffic file.

CQ is the measure of rotation which indicates how far the crossing speed distribution is shifted because of the effect of crossing maneuvers.

And

$$CVQ = V'_{3m}{}^{CQ} - V_{0m}{}^{CQ}$$

Where V'_{3m} is the median block crossing speed which is obtained on superimposing the effect of crossing impedance in the median block speed V_{3m}.

And

V_{0m} is the median basic desire speed.

Thus the CQ value is a very important parameter in the simulation program. CQ values have been calibrated for different types of vehicles involved in crossing, on both plain and rolling terrain's, and for both single and intermediate lane roads [11].

CHAPTER 3

ANALYSIS OF PASSENGER CAR EQUIVALENTS

3.1 Introduction

The heterogeneity of traffic on Indian roads makes it difficult to find analytical relationships between speed and flow. It is generally observed that the road space on Indian roads is utilized by the slow and fast moving vehicles at the same time. Also, the traffic interactions are more complex to observe and study, as no segregation of traffic is prescribed or followed on most of the Indian roads.

Different types of vehicles have their own characteristics such as speed, dimensions, flow logic, power to weight ratio and response to the presence of other vehicles. In addition the traffic composition varies from one place to the other (like urban and rural) and no one vehicle can really be considered as the predominant class for the entire country at present. We can take solace in the fact that the Maruti vehicle (car, van, etc.,) is fast dominating the scene in most of the urban and to some extent rural areas. Keeping this in view, Maruti Car is taken as the standard vehicle for all computational and comparison purposes in the present work.

The crux of the problem thus lies in developing speed-flow relationship involving such complex mix of vehicle types. From the above discussion it is also clear that, while developing speed-flow relationships we cannot simply add the numbers of different vehicle types to give the flow. A method has to be devised to present the actual effect of the heterogeneous traffic on the speed and behavior of different class of vehicles in the stream.

If we can convert vehicles of different types into a standard vehicle based on some criteria, the problem is solved. Usually the standard vehicle is taken as a passenger car and the conversion factor, which converts all vehicles into equivalent number of passenger cars, is called the PCE (Passenger Car Equivalent).

3.2 Definition of PCE

As explained in the previous section, the basic idea behind the concept of PCE is to determine the relative effect of different types of vehicles on the traffic flow as compared to a standard vehicle.

Though this idea seems to be fairly simple, the exact definition of PCE is not. In fact many definitions are possible and are practiced by different authorities. Some of the definitions are discussed below.

3.2.1 Definition in terms of Speed

A common definition is the one adopted in U. K [9] and is as follows:

If the addition of one vehicle per hour in the traffic stream reduces the average speed of the remaining vehicles by the same amount as the addition of, say, 'X ' cars per hour, then one vehicle of that type is considered equivalent to 'X ' PCE's.

The above definition emphasizes that the relative hindrance of any vehicle other than a car is to be taken in terms of its effect on speed alone.

3.2.2 Definition in Relation to Capacity

The 1965 Highway Capacity Manual follows a definition that is related to the capacity of a road.

In the words of the manual:

"Trucks reduce the capacity of a Highway in terms of total vehicles carried per hour. In effect each truck displaces several passenger cars in the flow. The number of passenger cars that each dual-tyred vehicle represents under specific conditions is termed as passenger car equivalent for these conditions".

This definition is more general and paves the way for calculating the PCE by different methods, which may lead to different results.

3.3 Earlier Work done in India

In India very little work has been done on this front. In fact until RUCS has been carried out practically no work has been done even for developing speed-flow relationships on Indian highways.

PCE values are calculated for different types of highways (Single as well as Multilane) and for different type of terrains in RUCS. The PCE values as suggested by RUCS are given in Table 3.1.

Although RUCS has been updated recently no attempt has been made to re calibrate PCE values; but IRC has revised PCE values from what they are suggested in RUCS, in its recent guidelines for capacity of roads in urban and rural areas [4],[5]. These guidelines didn't mention as how these values are arrived at. The guide lines for capacity analysis on urban roads although acknowledge that the PCE value of a vehicle is dependent on its percentage composition in the traffic takes into account only two different compositions of a vehicle (less than or equal to 5% and greater than 10 %) into account. The PCE values as recommended by IRC guidelines are given in Tables 3.2 and 3.3.

Table 3.1 PCE Values as Suggested in RUCS [10]

S. No	Vehicle Type	PCE Value
1.	Car	1
2.	Bus	3 In Plain Terrain 4 In Hilly Terrain
3.	Truck	3 In Plain Terrain 4 In Hilly Terrain
4.	Tempo/Auto	4 In Plain Terrain 5 In Hilly Terrain
5.	Tractor Trailer	4 In Plain Terrain 5 In Hilly Terrain
6.	2-Wheelers	0.75
7.	Bicycle	0.25
8.	Cycle rikshaw	1
9.	Bullock cart	6
10.	Horse cart	4

Table 3.2 Recommended PCE factors for Various Types of Vehicles on Urban Roads [5]

S. No	Vehicle Type	PCE Factor % Composition of vehicle type in traffic stream < 5%	10 % and Above
1.	Motor Cycle or Scooter	0.50	0.75
2.	Passenger Car:Pickup Van	1.00	1.00
3.	Agricultural Tractor;Light Commercial Vehicle	1.20	2.00
4.	Auto rickshaw	1.40	2.00
5.	Light commercial vehicle	2.20	3.70
6.	Truck or Bus	4.00	5.00
7.	Bicycle	0.40	0.50
8.	Cycle rickshaw	1.50	2.00
9.	Horse cart	1.50	2.00
10.	Hand cart	2.00	3.00

Table 3.3 Recommended PCE factors for Various Types of Vehicles on Rural Roads [4]

S. No	Vehicle Type	PCE Factor
1.	Motor Cycle or Scooter	0.50
2.	Passenger Car:Pickup Van	1.00
3.	Agricultural Tractor;Light Commercial Vehicle	1.50
4.	Truck or Bus	3.00
5.	Truck-trailer, Agricultural Tractor-trailer	4.50
6.	Bicycle	0.50
7.	Cycle rickshaw	2.00
8.	Hand cart	3.00
9.	Horse drawn Vehicle	4.00
10.	Bullock cart	8.00

3.4 Present Work

3.4.1 The Concept of Vehicle Throughput

Simply stated the throughput of a stream of traffic represents the number of vehicle kilometers of distance traveled by the stream in a unit interval of time.

Let's say that X_i vehicles of vehicle type i pass a section of length S with an average speed V_i in a unit interval of time. Then the throughput of this stream can be written as

$$\text{Throughput} = X_i V_i \qquad \text{...(3.1)}$$

Generalizing for a mixed traffic with vehicle types (i = 1..N)

the throughput is given as

$$\text{Throughput} = \sum_{i=1}^{N} X_i V_i \qquad \text{...(3.2)}$$

The vehicle throughput is an index of productivity achieved under the prevailing roadway and traffic conditions and as such much more superior to flow. The computation of this has been made possible by the simulation model as traffic process are monitored throughout the stretch and not at a point only as is possible in field studies.

3.4.2 Computation of PCE Values based on Number of Cars displaced by Truck/Bus/Tractor in an all Maruti Car Stream

Let's consider an all Maruti Car stream at a particular flow level. The throughput increases as the flow increases, reaches a maximum value and then starts decreasing (See Figure 3.1). If we now introduce some trucks into the all Maruti Car stream replacing them by about 10 % the throughput-flow variation follows the same pattern but the maximum throughput achievable in the second case becomes less compared to the first case.

The flow-throughput variation of all Maruti Car stream and that with 10 % trucks in it are presented in Figures 3.1 and 3.2 respectively. Assuming that throughput varies in a non-linear manner with flow, polynomial of the form $y = a + b*x + c*x^2$ was fitted to the above curves. It can be observed from these figures that the maximum throughput in Fig 3.2 is considerably less than that of Fig 3.1 (Assuming that the maximum throughput in Fig 3.1 corresponds approximately to a flow of 1200 veh/hr). Also it can be noted that the number of vehicles passed corresponding to these maximum throughputs is also different and is approximately 1000 vehicles. This reduction in throughput and the corresponding decrease in number of vehicles carried is due to the addition of 10 % trucks into the stream. Let's define the PCE of a vehicle as the number of passenger cars displaced by that vehicle when introduced into the stream. Following this definition the PCE of truck can now be calculated as follows.

Equating the maximum number of vehicles passed in the first case and the second case (∵ The maximum throughput and the number of vehicles should have been the same if 10 % Trucks are not there)

1200 Maruti Cars = 1000 Vehicles

1200 Maruti Cars = 900 Maruti Cars + 100 * PCE of Truck

=> 1 Truck ≡ 3 Maruti Cars at 10 % composition in the stream

and at 1000 Veh/hr flow level

The above value is arrived at by comparing the number of vehicles at the respective maximum throughputs. If the same process is repeated for 10 % reduction from maximum throughput etc., we can get PCE at different flow levels corresponding to a particular composition of trucks in the stream.

The above process is repeated by varying truck percentage in the stream upto 100 % in steps of 10 %. The flow-throughput variations are shown in Figure 3.3 and the PCE values can be read from Table 3.4.

The above procedure is repeated by introducing bus and tractor in the stream and the PCE values are found. The flow throughput variations are shown in Fig 3.4 and 3.5 respectively for bus and tractor and the PCE values are shown in Table 3.6 and 3.8. The variation of PCE with flow is plotted for truck, bus and tractor. These are shown in Figures 3.6 to 3.8.

The results indicate that the PCE of truck, bus, tractors reduce as the proportion of them increases in the traffic stream. This seems to be a paradox. This is because the PCE of a vehicle has been defined as number of cars replaced by that particular vehicle. Also this method doesn't take into account the speed differential among the individual vehicles of the stream. One more method of PCE using the number of vehicles passed and the speed as the criteria is discussed in section 3.6.

3.5 Computation of PCE values using Equivalent Vehicle Throughput Concept

Let's consider an all Maruti Car stream at a particular flow level, say F. According to the definition given in section 3.4, this stream will be having a particular throughput say 'X' veh-km/hr. If trucks are introduced into this stream at, say, P percent of the original flow, F, then throughput of the stream will reduce to 'Y' veh-km/hr. This reduction in throughput is due to the addition of trucks. It should also be noted that the throughput 'Y' consists of two components, the throughput of Maruti Cars (Y_M) and the throughput of trucks (Y_T). Using the concept of equivalent vehicle throughput the PCE of truck (or any other vehicle) at the flow F and at P percentage composition of trucks can be computed as follows.

$$X = Y_M + Y_T * \text{PCE of truck} \quad ..(3.3)$$

$$=> \quad \text{PCE of truck} = (X - Y_M / Y_T)$$

Since throughput at any flow level is calculated using the number of vehicles passed and the average speed of them, this method implicitly takes into account the speed differential among vehicles and also the number of vehicles actually passed at any particular instant

PCE values have been calculated for truck and tractor using this method and the results are shown in Tables 3.10 and 3.11. The results are plotted with flow as abscissa and PCE of vehicle as ordinate. The graphs are shown in Figures 3.9 and 3.10. To show how PCE of a vehicle is varying with increase in percentage of truck and tractor, graphs are plotted with percentage truck as abscissa and the PCE of the vehicle as ordinate. These are shown in Figure 3.11 and 3.12 respectively for truck and tractor.

The results show that the PCE of a vehicle increases with flow level in a non linear manner. With the increase in percentage of trucks or tractors the PCE values first increases and then they start decreasing indicating that addition of trucks will no longer be effective after some point. This aspect is investigated in detail in section 3.8.

3.6 Simulation Experiments for Computation of PCE Values

A perfectly level single lane road stretch of 5 Km in length is taken for the study. A road file has been prepared which corresponds to these conditions. At each flow level traffic has been generated first with Maruti Cars in both directions. The Maruti Cars are then replaced by the vehicle whose PCE value is to be computed, in steps of 10% varying from 10 to 100% and the traffic is again generated. After each traffic file has been generated, the main simulation has been run to produce the event file, which is then given as input to the

results processing program which gives apart from other things the average speed of each vehicle and the number of vehicles of each vehicle which have passed the section under consideration in the time interval selected. The throughput of the stream can be calculated using Eq 3.2. The values are for the 5 Km stretch. The PCE values are computed using the above two methods. It must be noted that the PCE values calculated are applicable for these road conditions only, i. e, single lane and level terrain.

The flow is now incremented and the above process is repeated to get the PCE value of a vehicle at different flow levels.

3.7 General Discussion on Results of PCE Values

The results on PCE values reinforce the notion that PCE value of a vehicle differ with composition, flow etc., and that a single PCE value should not be used for the purpose of capacity analysis. As shown in Tables 3.1 to 3.3, the peasant standards prevailing in India doesn't take this into account. The values suggested in RUCS and other IRC guide lines doesn't mention as to what composition and flow these values correspond to. For this reason the present PCE values couldn't be compared with any of the above values. One reason why the researchers and planners couldn't consider this aspect is the huge amount of data, that is required for generating a PCE matrix. But the present work reinforces the advantages simulation has to offer in these types of situations and a beginning can be made now in this direction to further investigate this concept of PCE.

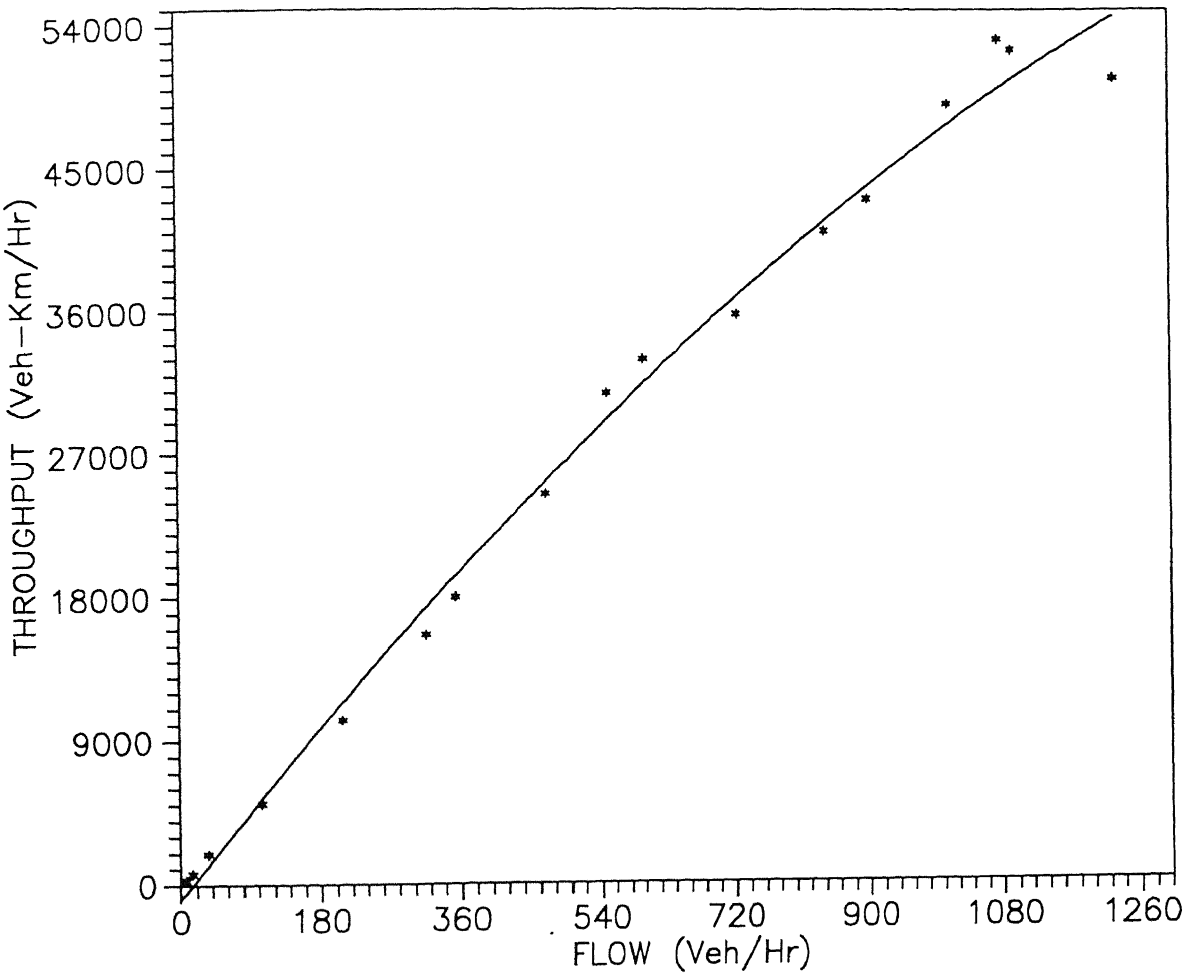

Fig. 3.1 Variation of Throughput with Flow for all Maruti Car Stream

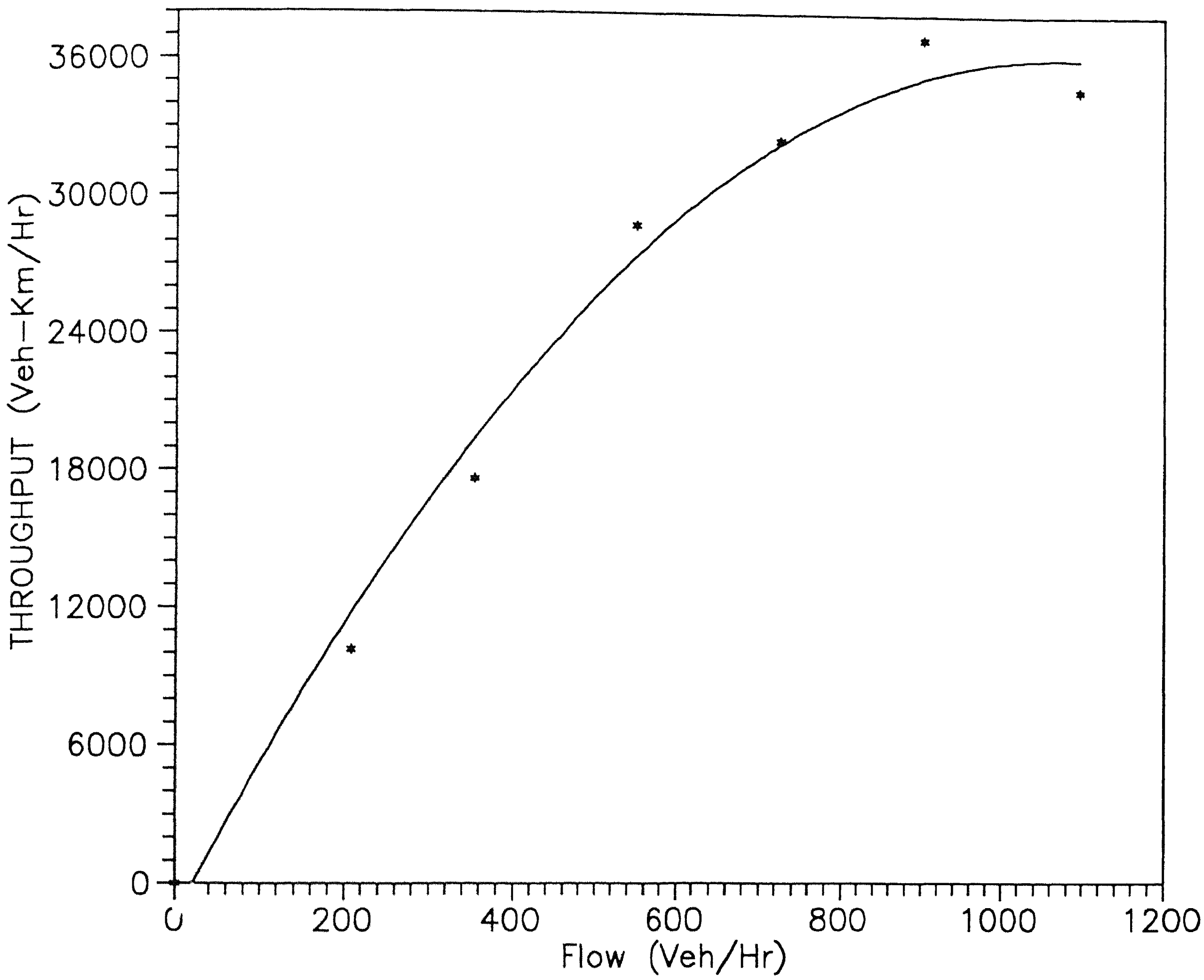

Fig.3.2 Variation of Throughput with Flow when 10 % Trucks are introduced in all Maruti Car Stream

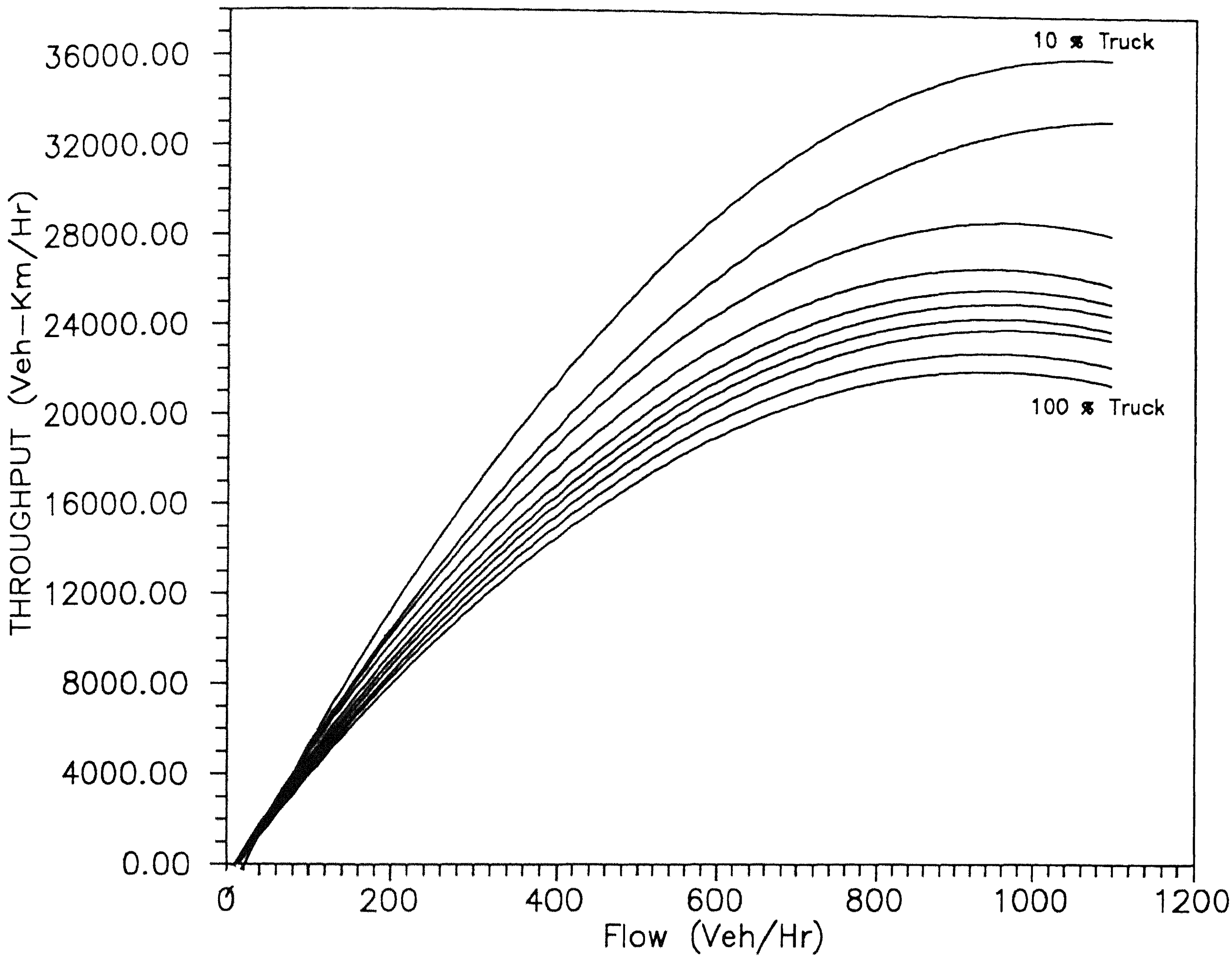

Fig.3.3 Variation of Throughput with Flow for different composition of Trucks in all Maruti Car stream

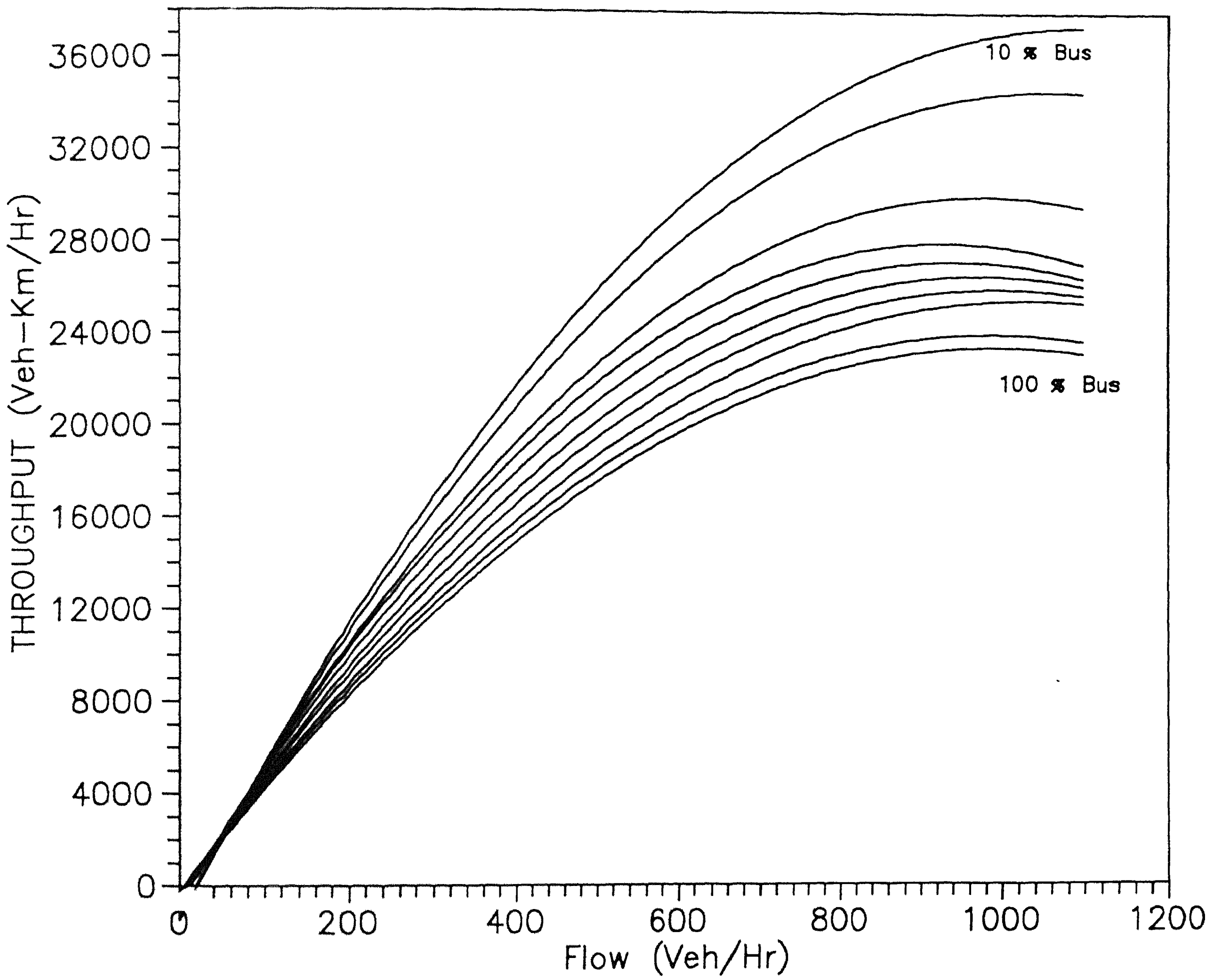

Fig.3.4 Variation of Throughput with Flow for different composition of Buses in all Maruti Car Stream

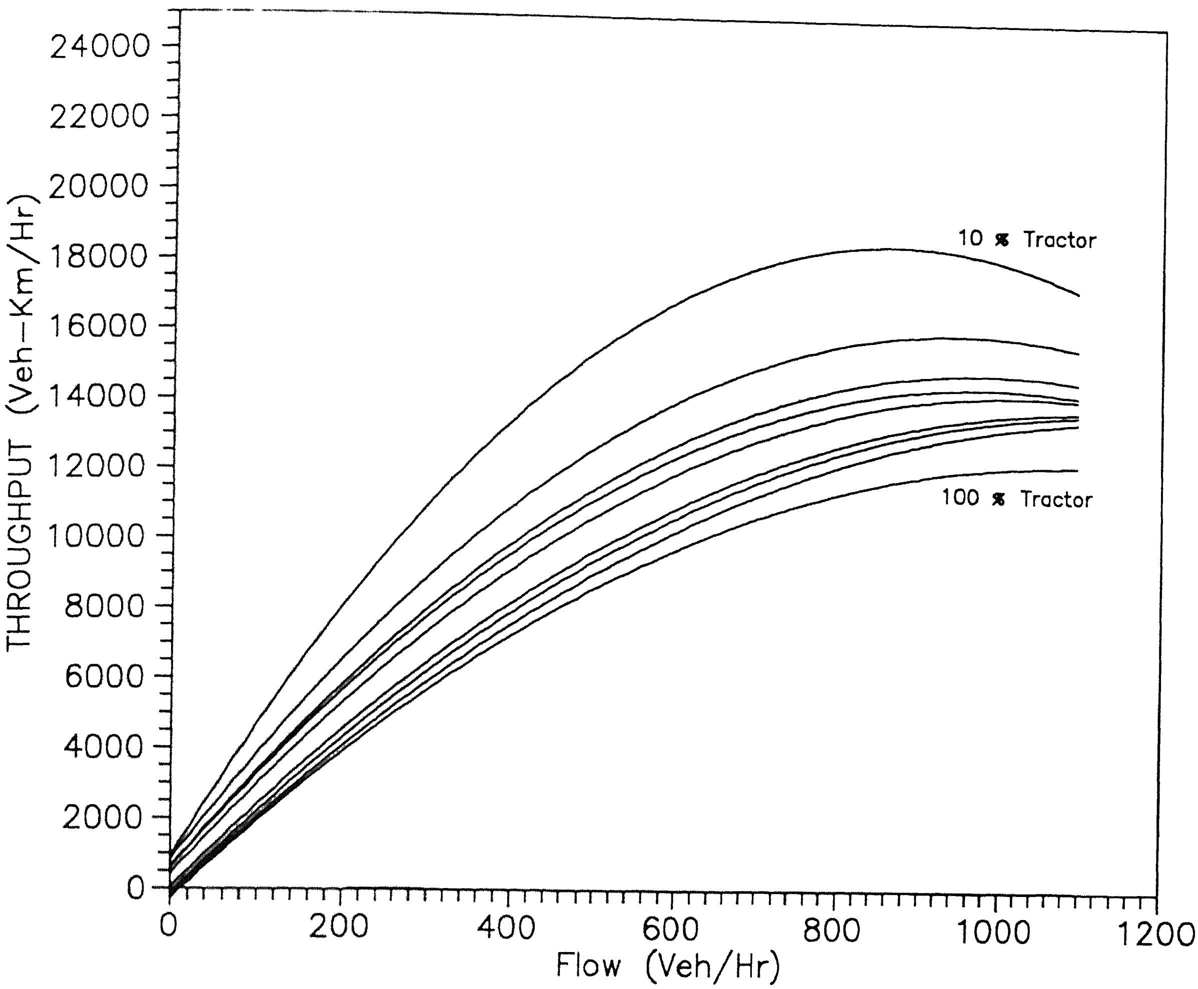

Fig.3.5 Variation of Throughput with Flow for different composition of Tractors in all Maruti Car Stream

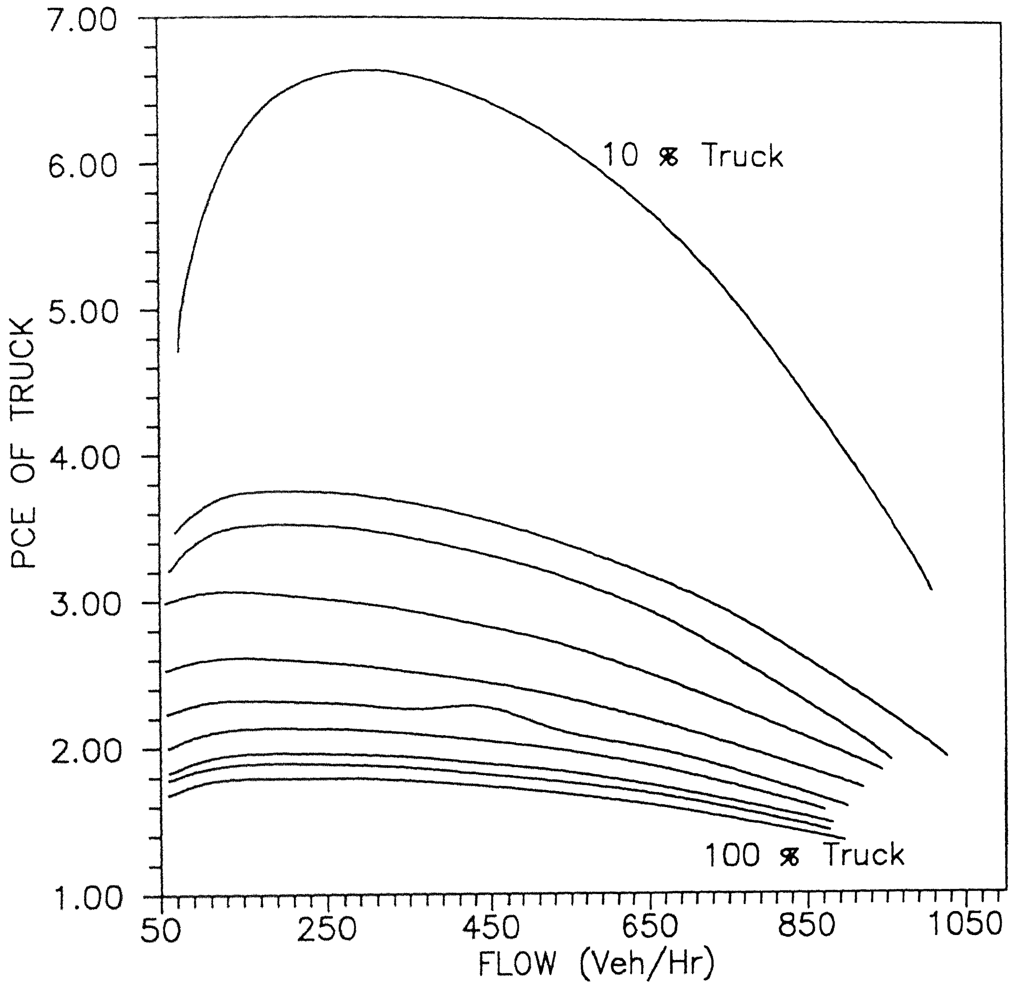

Fig.3.6 PCE values of Truck at different Flow levels for different Compositions (Method-1)

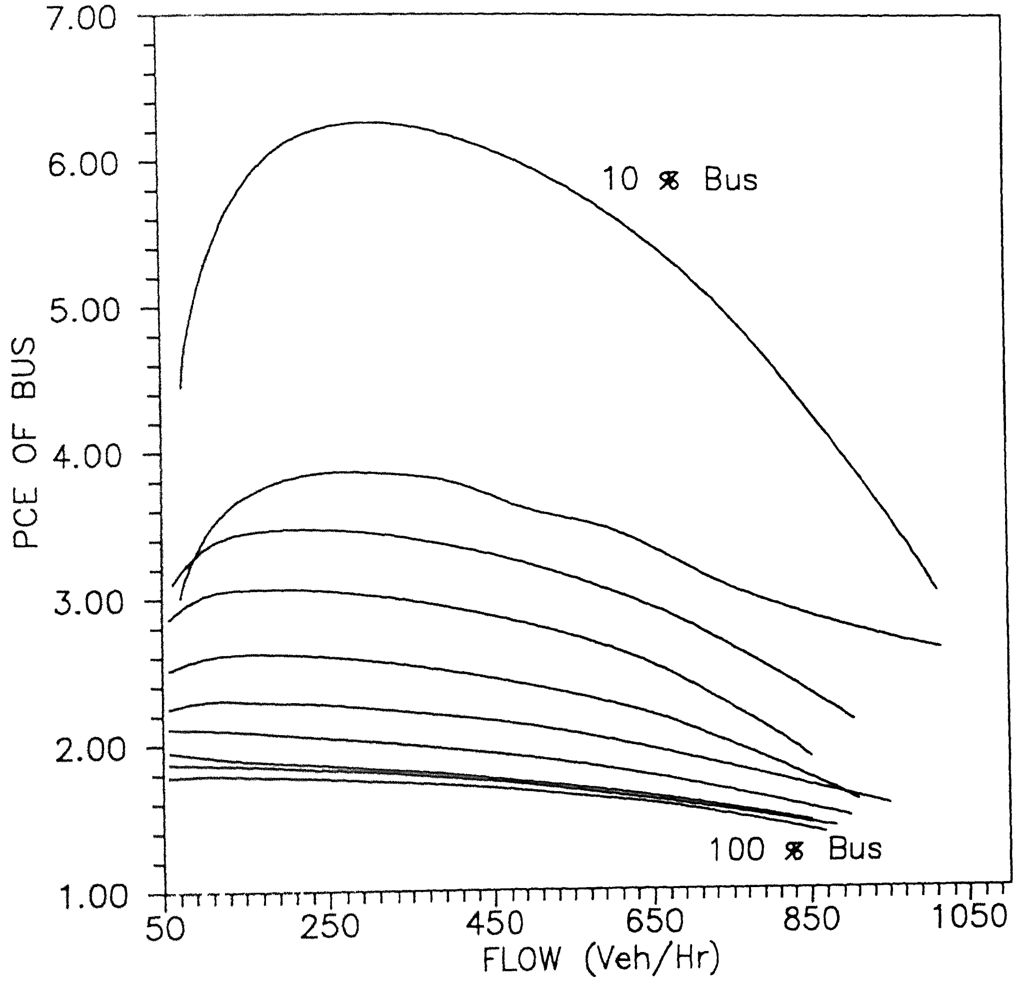

Fig.3.7 PCE values of Bus at different Flow levels for different Compositions (Method-1)

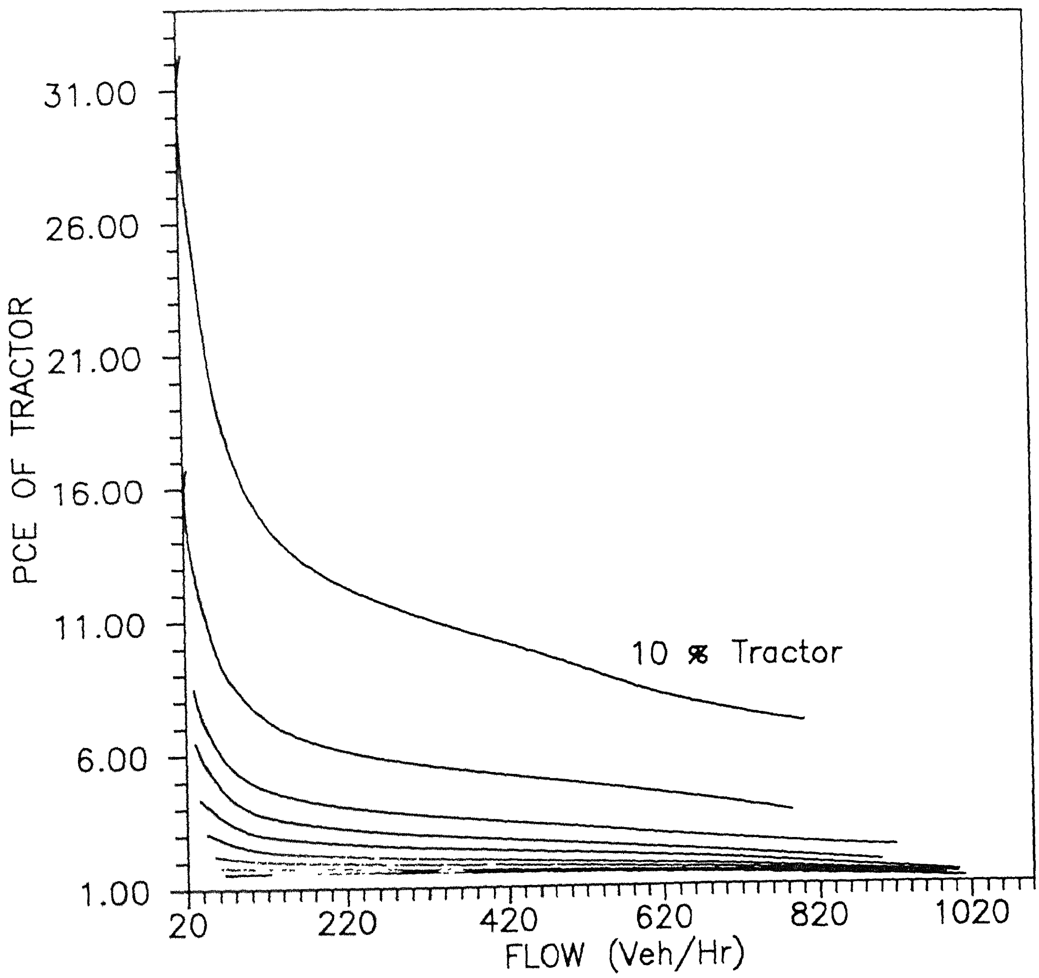

Fig.3.8 PCE values of Tractor at different Flow levels for different Compositions (Method-1)

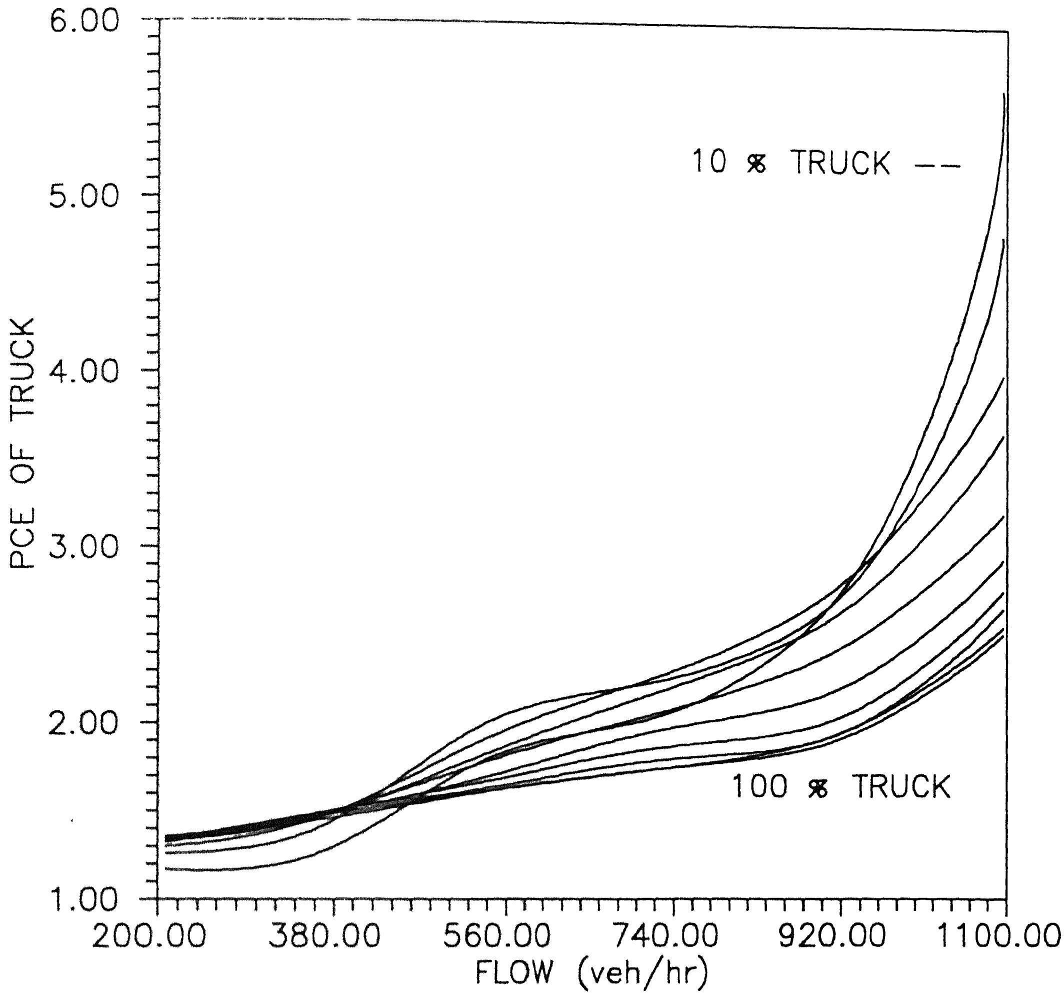

Fig.3.9 PCE values of Truck at different Flow levels for different Compositions (Method-2)

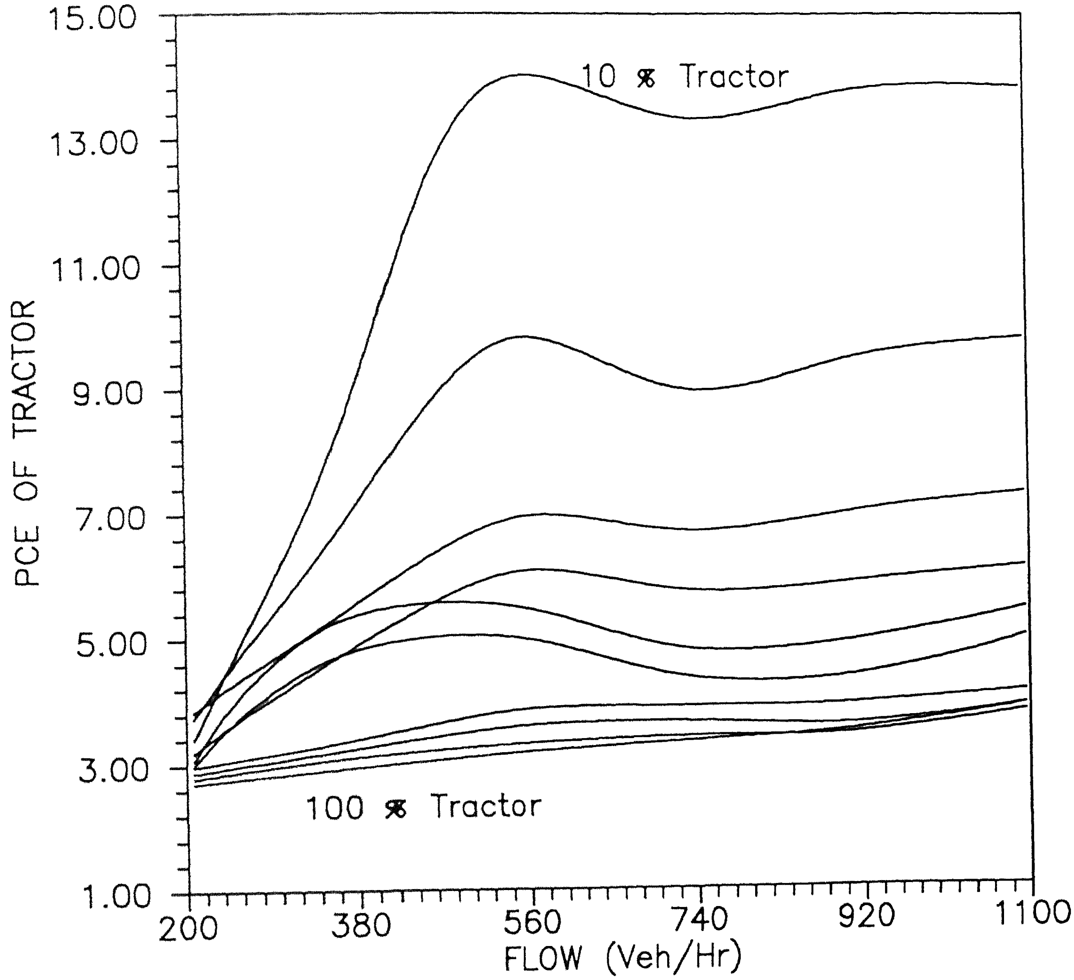

Fig.3.10 PCE values of Tractor at different Flow levels for different Compositions(Method-2)

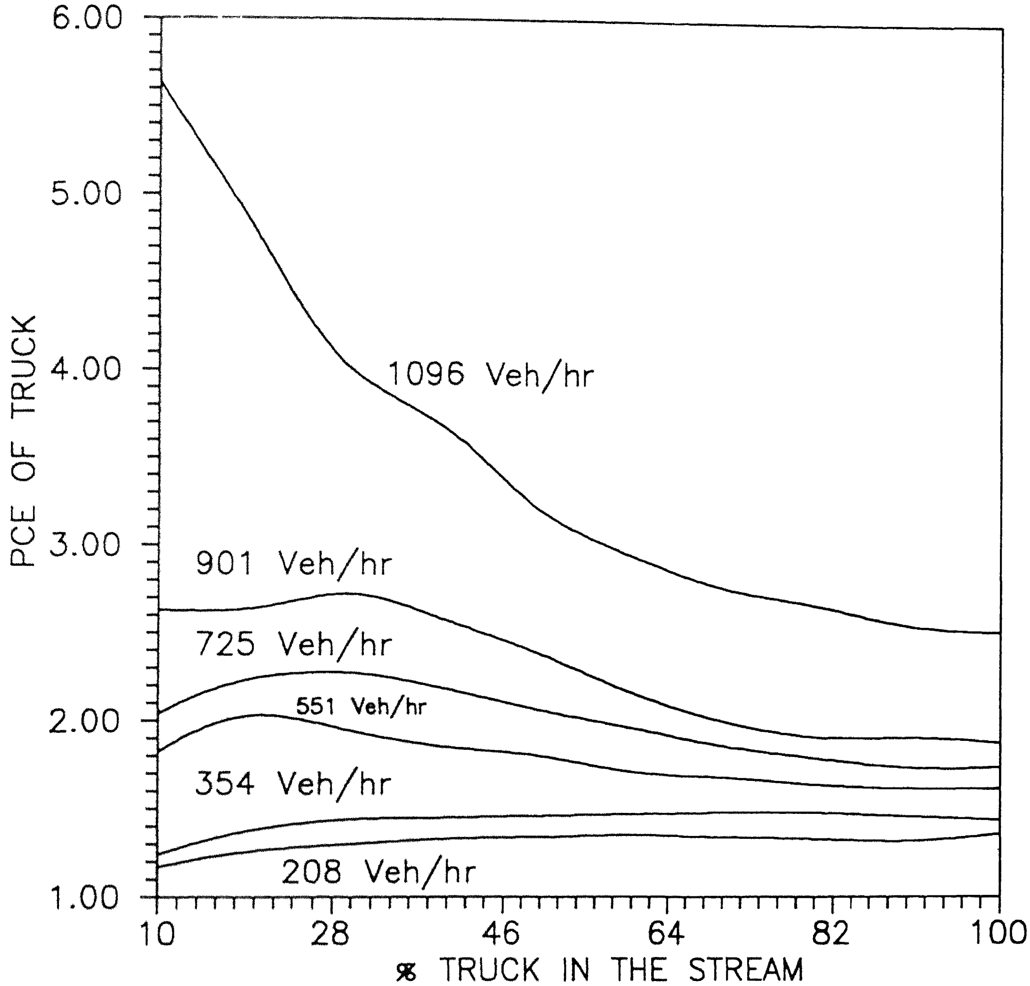

Fig.3.11 PCE values of Truck for different compositions at different Flows (Method-2)

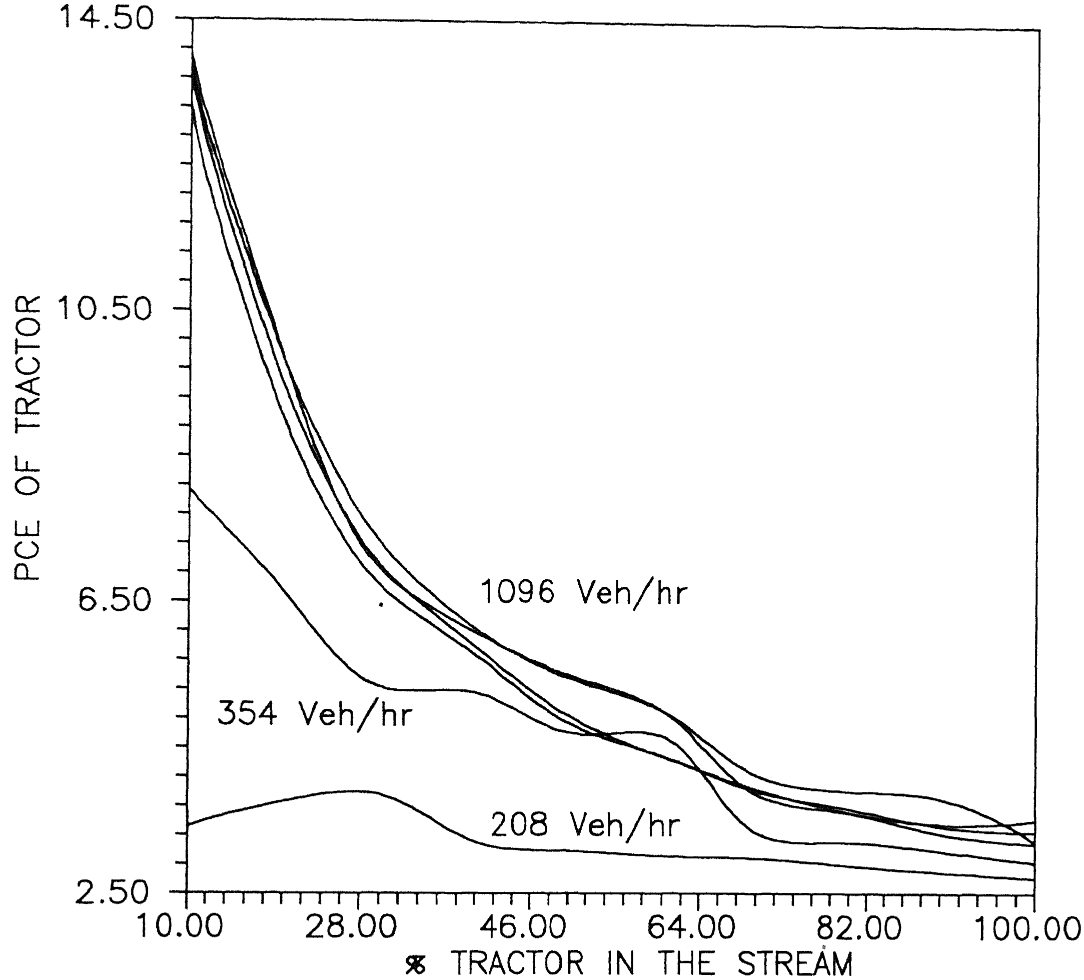

Fig.3.12 PCE values of Tractor for different compositions at different Flows (Method-2)

Table 3.4 PCE of Trucks using the concept of number of cars displaced by Truck

% Truck in Stream	Percent reduction in throughput from maximum throughput									
	10 %	20 %	30 %	40 %	50 %	60 %	70 %	80 %	90 %	100 %
10	4.71	6.00	6.45	6.61	6.63	6.53	6.32	5.95	5.27	3.07
20	3.47	3.71	3.75	3.74	3.69	3.60	3.46	3.26	2.92	1.93
30	3.21	3.46	3.52	3.52	3.49	3.42	3.32	3.17	2.90	1.91
40	2.99	3.06	3.06	3.03	2.99	2.93	2.84	2.72.	2..50	1.84
50	2.53	2.60	2.61	2.59	2.56	2.51	2.45	2.35	2.18	1.72
60	2.23	2.31	2.32	2.31	2.29	2.26	2.20	2.12	1.99	1.59
70	2.00	2.10	2.13	2.13	2.12	2.09	2.05	1.99	1.88	1.57
80	1.83	1.93	1.96	1.96	1.95	1.93	1.89	1.84	1.74	1.48
90	1.78	1.86	1.89	1.89	1.88	1.86	1.82	1.77	1.69	1.43
100	1.68	1.77	1.79	1.79	1.79	1.77	1.74	1.69	1.61	1.36

Table 3.5 The flow values (veh/hr) corresponding to the above PCE values (Truck)

% Truck in Stream	Percent reduction in throughput from maximum throughput									
	10 %	20 %	30 %	40 %	50 %	60 %	70 %	80 %	90 %	100 %
10	74	131	191	255	325	403	491	595	730	1008
20	68	127	190	258	331	412	504	612	752	1026
30	61	112	168	227	291	362	443	538	664	956
40	57	108	162	220	283	353	433	527	651	944
50	58	109	163	222	286	356	437	532	656	920
60	59	110	164	223	287	357	437	531	654	900
70	60	111	165	222	285	355	433	526	646	871
80	61	113	167	225	289	359	439	532	653	881
90	60	110	164	222	284	353	432	524	644	877
100	60	111	165	222	285	354	432	526	646	895

Table 3.6 PCE values for Bus using the concept of number of cars displaced by Bus

% Bus in Stream	Percent reduction in throughput from maximum throughput									
	10 %	20 %	30 %	40 %	50 %	60 %	70 %	80 %	90 %	100 %
10	4.45	5 67	6.09	6.24	6.25	6.15	5.95	5.60	4.95	3.03
20	3 10	3 60	3.79	3.86	3.85	3 79	3.67	3.47	3.10	2.64
30	3.01	3.38	3.46	3.47	3.45	3.39	3.30	3.15	2.90	2.15
40	2.86	3.03	3.06	3.06	3.03	2.98	2.90	2.78 .	2.56	1.90
50	2.51	2.60	2.62	2.61	2.58	2.53	2.46	2.36	2.19	1.60
60	2.25	2.30	2.29	2.28	2.25	2.21	2.16	2.08	1.94	1.57
70	2.11	2.10	2.08	2.05	2.02	1.98	1.93	1.86	1.74	1.49
80	1.95	1.91	1.88	1.86	1.83	1.80	1.75	1.69	1.59	1.46
90	1.87	1.86	1.85	1.83	1.81	1.78	1.74	1.68	1.59	1.42
100	1.78	1.79	1.78	1.77	1.75	1.73	1.70	1.65	1.58	1.38

Table 3.7 The flow values (veh/hr) corresponding to above PCE values (Bus)

% Bus in Stream	Percent reduction in throughput from maximum throughput									
	10 %	20 %	30 %	40 %	50 %	60 %	70 %	80 %	90 %	100 %
10	76	134	195	262	334	413	503	609	747	1011
20	73	129	189	254	324	402	490	596	734	1015
30	63	114	170	229	293	365	445	541	664	904
40	58	108	162	219	281	349	427	520 .	641	850
50	58	109	163	221	285	355	434	529	653	910
60	58	110	166	226	291	362	444	541	666	950
70	57	111	168	230	297	371	454	555	685	900
80	58	114	173	237	306	383	470	573	708	850
90	57	111	167	228	295	368	452	551	680	880
100	57	110	166	226	291	362	443	539	660	867

Table 3.8 PCE values for Tractors using the concept of number of cars displaced by Tractors

% Truck in Stream	Percent reduction in throughput from maximum throughput									
	10 %	20 %	30 %	40 %	50 %	60 %	70 %	80 %	90 %	100 %
10	32.3	17.7	14.5	13.0	12.0	11.2	10.4	9.60	8.33	7.12
20	17.0	8.70	7.10	6.34	5.88	5.53	5.22	4.90	4.49	3.76
30	8.51	5.26	4.48	4.09	3.83	3.61	3.40	3.16	2.82	2.40
40	6.48	4.12	3.53	3.25	3.05	2.89	2.73	2.54	2.27	1.86
50	4.34	3.16	2.83	2.66	2.53	2.43	2.32	2.20	2.01	1.43
60	3.07	2.46	2.27	2.17	2.09	2.02	1.94	1.85	1.72	1.36
70	2.23	2.03	1.95	1.90	1.86	1.82	1.77	1.70	1.60	1.37
80	1.80	1.75	1.73	1.70	1.68	1.65	1.61	1.56	1.48	1.29
90	1.59	1.59	1.58	1.57	1.55	1.53	1.51	1.47	1.40	1.27
100	1.53	1.57	1.58	1.58	1.57	1.55	1.52	1.48	1.41	1.20

3.9 Flow values (veh/hr) corresponding to above PCE values (Tractors)

% Tractor in Stream	Percent reduction in throughput from maximum throughput									
	10 %	20 %	30 %	40 %	50 %	60 %	70 %	80 %	90 %	100 %
10	25	74	126	182	242	310	387	479	601	801
20	25	77	133	254	257	328	408	500	614	784
30	31	86	144	229	275	351	437	539	675	920
40	32	87	146	219	279	356	444	550 .	692	900
50	38	94	154	221	288	365	453	557	692	1003
60	46	104	167	226	307	389	480	589	729	1002
70	55	114	177	230	317	398	490	596	733	967
80	62	122	186	237	330	412	504	613	751	986
90	67	128	194	228	339	423	517	626	764	981
100	67	125	186	226	325	404	495	601	739	1011

Table 3.10 PCE values for Trucks using Equivalent Vehicle Throughput Concept

Flow ---> % Truck in the stream	208 veh/hr	354 veh/hr	551 veh/hr	725 veh/hr	901 veh/hr	1096 veh/hr
10	1.17	1.24	1.82	2.04	2.63	5.64
20	1.26	1.38	2.03	2.24	2.64	4.80
30	1.30	1.44	1.94	2.27	2.72	4.00
40	1.33	1.45	1.85	2.18	2.57	3.66
50	1.34	1.46	1.80	2.06	2.38	3.20
60	1.35	1.47	1.71	1.96	2.16	2.94
70	1.34	1.48	1.68	1.86	2.00	2.76
80	1.33	1.48	1.64	1.79	1.91	2.66
90	1.32	1.46	1.62	1.74	1.91	2.55
100	1.36	1.44	1.62	1.74	1.88	2.51

Table 3.11 PCE values for Tractors using Equivalent Vehicle Throughput Concept

Flow ---> % Tractor in the stream	208 veh/hr	354 veh/hr	551 veh/hr	725 veh/hr	901 veh/hr	1096 veh/hr
10	3.41	8.03	14.01	13.34	13.76	13.84
20	3.75	6.63	9.81	8.98	9.45	9.80
30	3.85	5.32	6.94	6.71	6.99	7.30
40	3.20	4.67	6.07	5.76	5.87	6.12
50	3.08	5.25	5.49	4.83	4.93	5.45
60	3.01	4.70	5.00	4.38	4.37	5.00
70	2.98	3.33	3.86	3.90	3.93	4.12
80	2.88	3.20	3.60	3.66	3.61	3.90
90	2.79	3.08	3.32	3.42	3.45	3.80
100	2.71	2.92	3.18	3.34	3.50	3.90

3.8 Study of the Effect of each Incremental Addition of Truck, Bus and Tractor on the Behavior of the Traffic Stream

Taylor, Miller and Ogden [12], suggest, based on the simulation techniques that the proportion of trucks in the flow does not significantly affect speeds for gradients below 3 percent. They also suggest an upper limit for the proportion trucks in the traffic stream above which the effect of an increasing proportion of trucks is not as great. This critical proportion was found to lie between 5 and 8%, the higher value corresponding to higher gradients. However, since speed alone does not represent the effect of trucks on the traffic stream and also to study the upper limit above which the addition of trucks in not as great, it was decided that the parameter, acceleration noise (see below for definition) which essentially indicates the jerkiness/smoothness [3] of the flow be studied to get a clear picture of the variations in the traffic stream as the proportion of truck /bus/tractor increases.

3.8.1 Definition of Acceleration Noise and Methodology of Computation

The acceleration noise (broadly defined as the standard deviation of accelerations of a vehicle) can be considered as the disturbance of vehicle's speed from a uniform speed, or can be identified as a measurement of the smoothness of traffic flow.

Since the simulation model gives the speed profile of any vehicle, acceleration noise can be easily computed using the following equation given by Drew [3]

$$\sigma = \frac{(\Delta v)^2}{T} \sum_{i=0}^{T} \frac{n^2}{\Delta t i} \qquad \text{....(3.4)}$$

where

σ = Acceleration noise of a vehicle in m/s^2

T = Total Journey time in seconds

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where

σ = Acceleration noise of a vehicle in m/s^2

T = Total Journey time in seconds

Δv = change in velocity of interest (in m/s)

n = number of changes of Δv in time Δt_i

3.8.2 Results and Interpretation of Variation of Acceleration Noise

Tables 3.12 to 3.14 give the variation of acceleration noise of truck, bus and tractor at different flow levels and at different percentage composition of these vehicles in the base stream. These results are plotted with percentage composition of the vehicle as abscissa and acceleration noise as the ordinate. The curves are smoothened by spline curves.

Table 3.12 Acceleration Noise (m/s^2) Truck-Maruti Car stream at Different Flow Levels

% Truck	208 veh/hr	354 veh/hr	551 veh/hr	725 veh/hr	901 veh/hr
0	0.0080	0.0088	0.0090	0.0095	0.0090
10	0.1000	0.1400	0.2180	0.2450	0.2300
20	0.1150	0.2070	0.3000	0.2580	0.2500
30	0.1370	0.2170	0.3350	0.3120	0.2400
40	0.1540	0.2570	0.3340	0.2960	0.2350
50	0.1730	0.2590	0.3200	0.2860	0.2100
60	0.1920	0.2650	0.3130	0.2720	0.2000
70	0.2090	0.2560	0.2670	0.2560	0.1900
80	0.1900	0.2480	0.2410	0.2400	0.1850
90	0.1850	0.2250	0.2220	0.2000	0.1700
100	0.1810	0.2200	0.1940	0.1300	0.1250

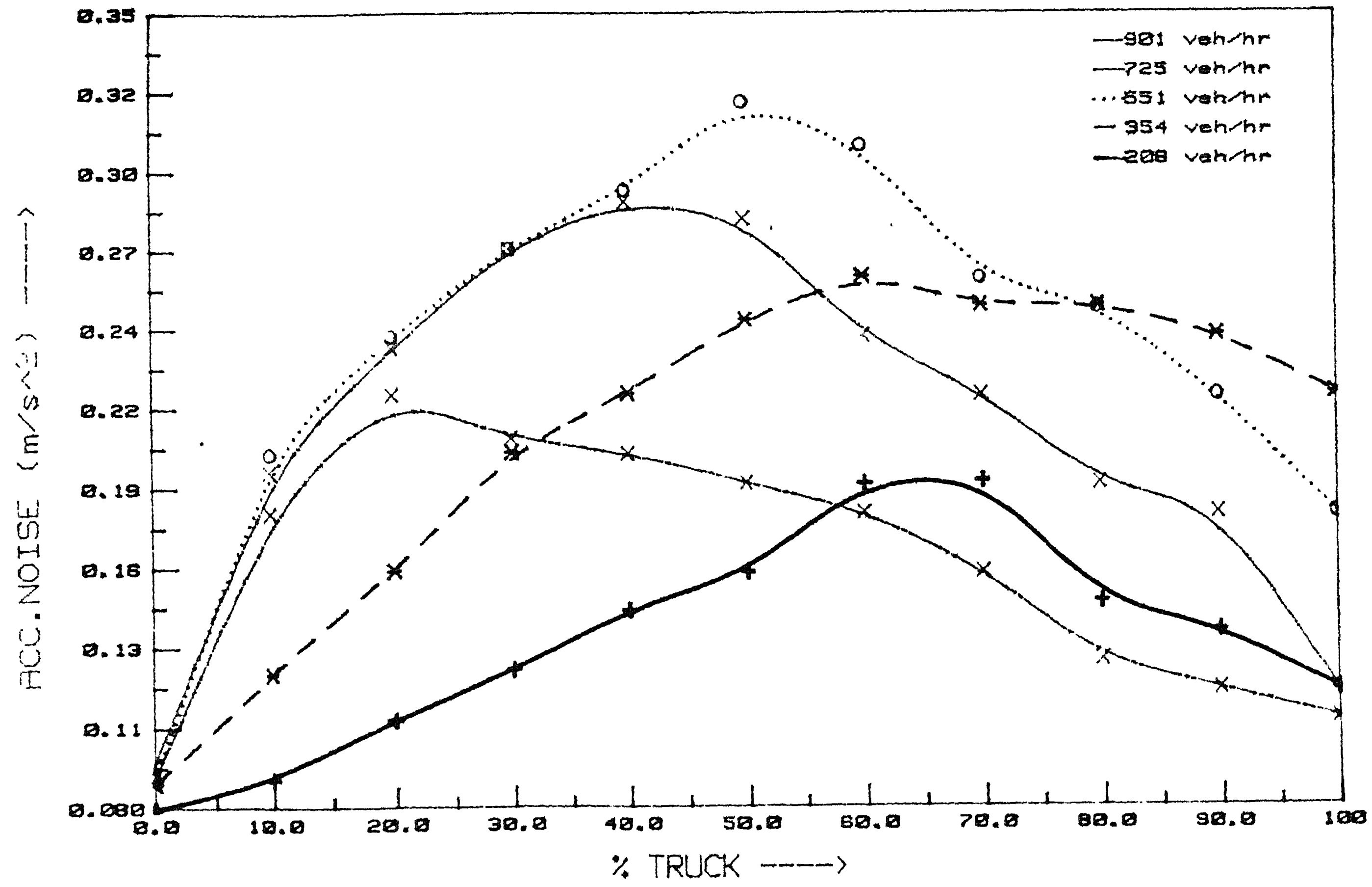


Fig. 3.13 Acceleration Noise of Truck - Maruti Stream for different Compositions at different Flows

Table 3.13 Acceleration Noise of Bus-Maruti Car Stream at Different Flow Levels

% Bus	208 veh/hr	354 veh/hr	551 veh/hr	725 veh/hr	901 veh/hr
0	0.0080	0.0088	0.0090	0.0095	0.0090
10	0.0900	0.1250	0.2000	0.1940	0.1800
20	0.1100	0.1600	0.2400	0.2360	0.2200
30	0.1270	0.2000	0.2700	0.2700	0.2050
40	0.1470	0.2200	0.2900	0.2860	0.2000
50	0.1600	0.2450	0.3200	0.2800	0.1900
60	0.1900	0.2600	0.3050	0.2400	0.1800
70	0.1910	0.2500	0.2600	0.2200	0.1600
80	0.1500	0.2500	0.2500	0.1900	0.1300
90	0.1400	0.2400	0.2200	0.1800	0.1200
100	0.1200	0.2200	0.1800	0.1200	0.1100

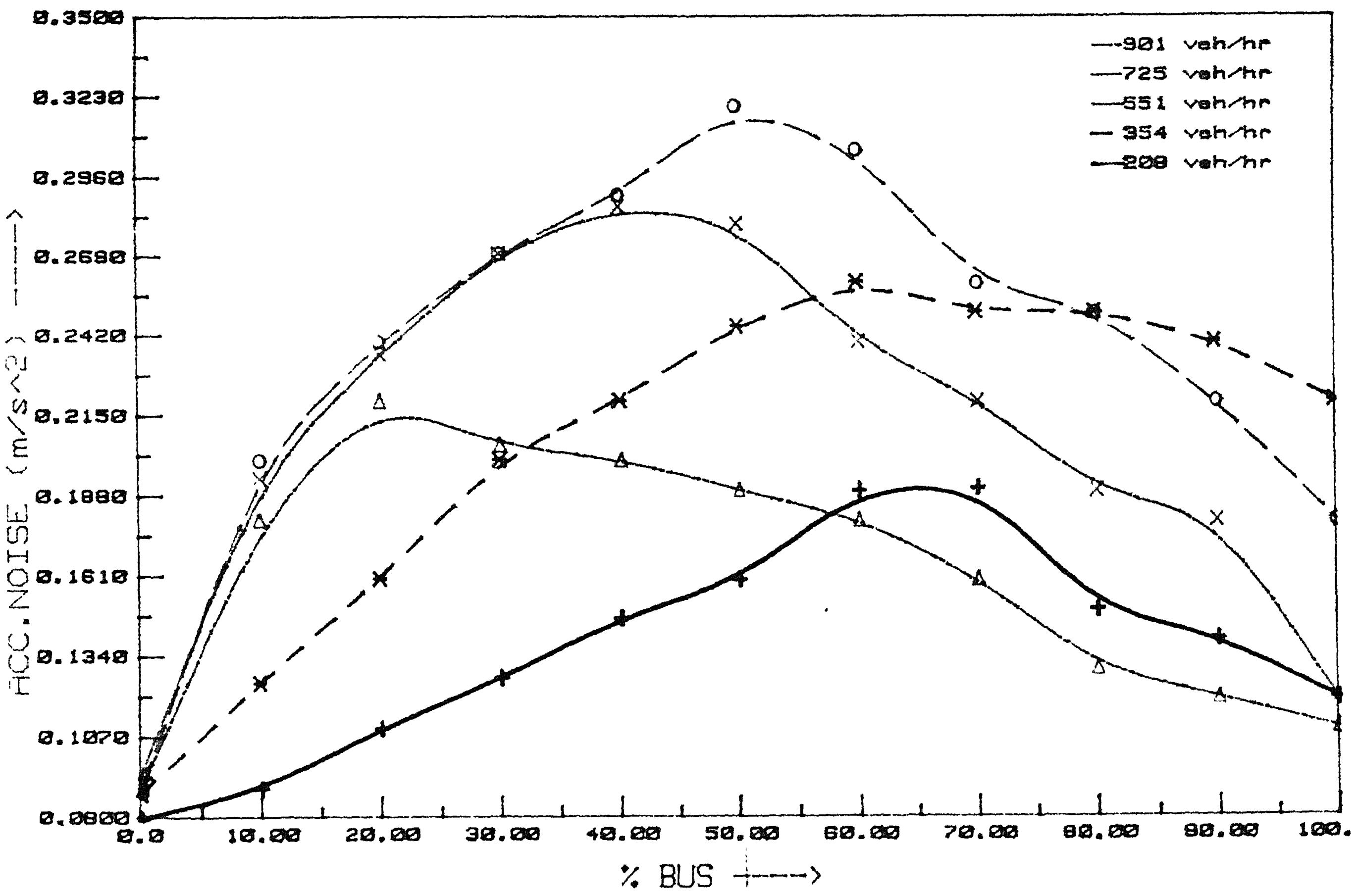


Fig. 3.14 Acceleration Noise of Bus - Maruti Stream for different Compositions at different Flows

The following conclusions can be drawn form the above graphs

- The peak of the acceleration noise curve shifts from right to left as the flow varies, indicating that the effect of adding truck/bus/tractor, prevails for longer duration (in terms of percentage of truck/bus/tractor) when the flow levels are less compared to higher flow levels.

- The effect of adding trucks and buses is approximately the same with truck causing more damage to flow compared to bus.

- The magnitude of acceleration noise is comparatively less when tractors are added to the stream, which can be explained by the fact that tractors have little accelerating capability.

- The upper limit for the addition of trucks/busses/tractors, above which more addition of them is not as significant, depends heavily on the flow rate. For example for trucks this percentage varies from 70 at 208 veh/hr flow to 20 at 901 veh/hr flow.

CHAPTER 4

CAPACITY ANALYSIS OF A IDEAL SINGLE LANE ROAD

4.1 Introduction

A critical need in traffic analysis is a clear understanding of the ability of various types of facilities to carry traffic. This knowledge when integrated with measurements of current traffic demand and forecasts of future traffic demand, allows the traffic engineer to plan and design facilities that can adequately serve society's needs.

Capacity analysis can be defined as the study of various types of highway facilities and their ability to carry traffic. Capacity analysis does not seek to identify merely the maximum amount of traffic that a facility can handle, but also the amounts of traffic that can be accommodated at various defined levels of operational quality. Thus capacity analysis is a part of every form of traffic analysis, including planning and design, operational analysis, analysis and evaluation of controls and analysis of alternatives.

4.1.1 The Level-of-Service Concept

The level-of-service is a letter designation that describes a range of operating conditions on a particular type of facility. The 1985 Highway Capacity Manual defines the level-of-service concept as "*a qualitative measure describing operational conditions within a traffic stream and their perception by motorists and/or passengers.*"

The above definition implies that the service quality should be described in terms that can be perceived by passengers. Several measures like speed, travel time, density, delay are used in 1985 Highway Capacity Manual. Apart from these parameters like acceleration noise, number of crossings per km, etc., which are not directly discernible to passengers, have also been used for defining level-of-service.

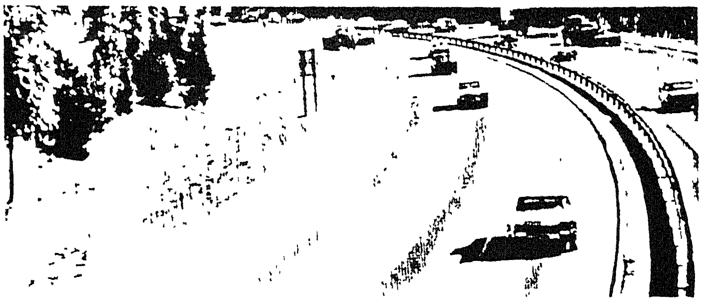
Six levels of service are defined for capacity analysis. They are given letter designation A through F, with level-of-service A representing the best range of operating conditions and the level-of-service F representing the worst operating conditions. In general, level-of-service A describes a free-flowing condition in which individual vehicles of the traffic stream are not influenced by the presence of other vehicles. level-of-service F generally describes breakdown operations which occur when flow arriving at a point is greater than the facility's capacity to discharge flow. At such points, queues develop, and level-of-service F exists with in the queue and at the point of breakdown. Levels of service B, C, D and E represent intermediate conditions, with the lower bound of level-of-service E often representing capacity operations. An illustrative diagram is shown in Fig 4.1 [7].

4.2 Earlier Work done in India

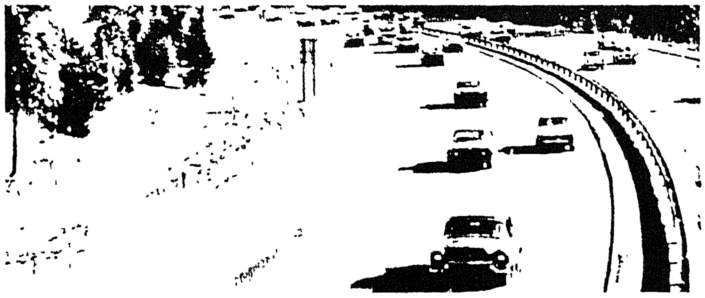
All the significant work done in India was carried out either during Road User Cost Study in 1980, or during the revision of RUCS in 1990.

Before 1980, practically very little research has been done on this important field. The Road User Cost Study, funded by the World Bank through Ministry of Surface Transport and implemented by the Central Road Research Institute,

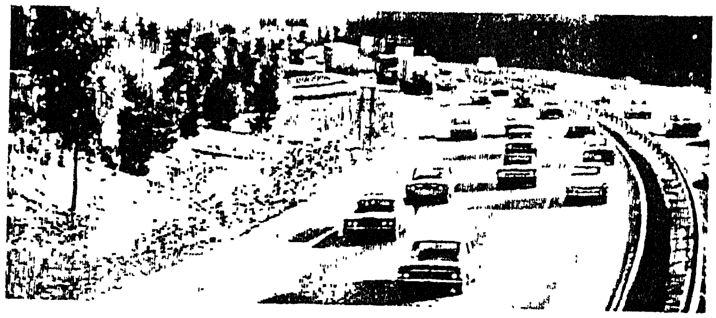
Level A
Free flow, no restrictions on maneuvering or operating speed



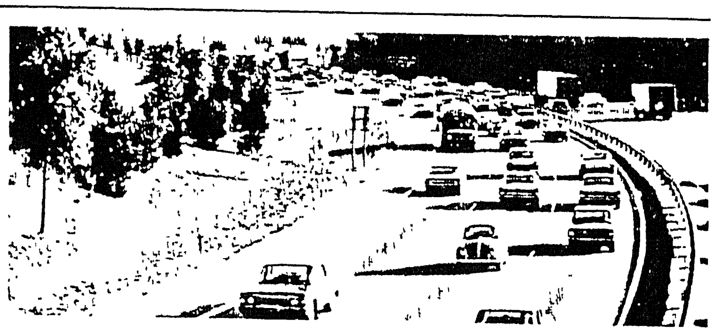
Level B
Stable flow, few restrictions



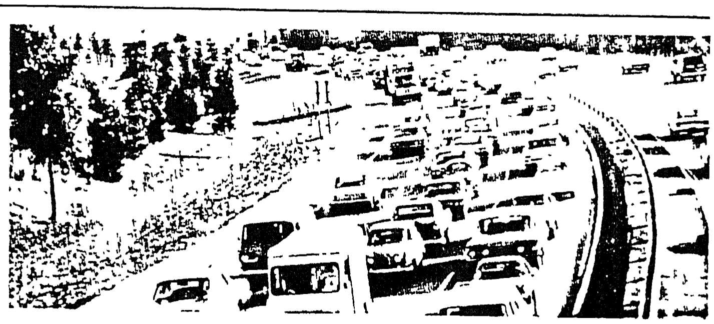
Level C
Stable flow, more restrictions



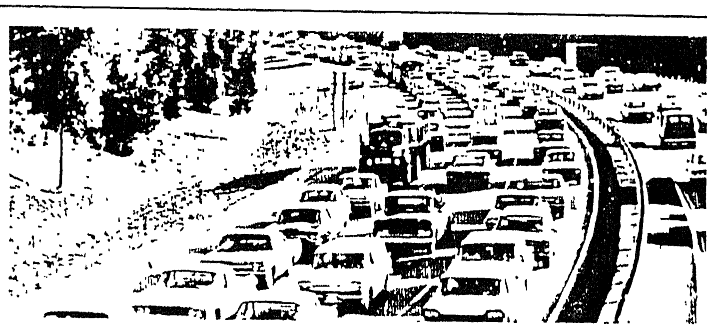
Level D
Approaching unstable flow



Level E
Unstable flow, some stoppages



Level F
Forced flow, many stoppages



took upon itself the task of conducting speed–flow studies in different parts of the country and collecting a wealth of data on roads of different widths. The other areas covered by RUCS are

- Determination of PCE for different vehicle types and under different road conditions.

- Collection and analysis of vehicle operating cost data

- Accident and fuel consumption study.

- Study of value of travel time savings.

Since 1980, vast changes have taken place in the transportation scenario in our country. The technology of vehicles itself has undergone major changes. The second important development that has taken place is the modernization of the road itself. Majority of the two lane highways are being converted into four lane highways.

Keeping in view these developments the Ministry of Surface Transport instituted a study for updating RUCS in collaboration with the Asian Development Bank.

The important conclusions arrived at during the revision of RUCS, as regards speed-flow research component of it are

- The speeds of vehicles on two lane and four lane roads have increase by 10-40 percent. The increase is partly due to improvements in vehicle technology and partly due to improvement in road conditions.

- Speeds of vehicles have not changed on single and intermediate lanes during the last decade, the narrow width dictating speeds.

- The drop in speed is much more pronounced now than in 1980.

- The capacity values as suggested in IRC guidelines need to reviewed.

The study is limited by the fact that it calculates capacities by taking PCE values from IRC guidelines which are only tentative.

4.3 Present Work

It is customary in the capacity analysis to calibrate capacity of a facility for ideal traffic, roadway and control conditions. These are then modified to account for prevailing conditions that are not ideal. Hence the present work focuses on the evaluation of capacity and description of level-of-service on an ideal single lane road. The following sections describe the methodology, implementation and results of the analysis.

As it is difficult to obtain percent time delay using the present form of output of the simulation model, it was decided that speed and density of the traffic stream be used for defining for level-of-service.

4.3.2 Methodology

For evaluating the capacity of an ideal single lane road, a single lane road with following road and traffic characteristics is assumed.

- Design Speed $\geq$ 60 Km/Hr
- 3.5m width carriage way
- 2m width shoulders on either side
- Level terrain
- 50/50 directional distribution of traffic
- All Maruti Cars in the traffic stream

The capacity of the single lane road is arrived at by studying the speed–throughput relationships. It is to be noted that throughout the study throughput is used instead of flow as the flow in this study will only represent the demand. For example if we send a flow of 200 veh/hr the resulting throughput of the stream is the manifestation of this flow and hence a better representative of the flow. Capacity of a

road section is defined as the flow (in PCE/hour) corresponding to the maximum throughput achievable. level-of-service is determined using speed and density as the main criteria. In a similar manner the change in level-of-service due to change in speed–throughput–density relationships with each incremental addition of truck, bus, and tractor are studied.

4.3.2.1 Computation of Density from Simulation Model Experiments

The density of a traffic stream is defined as the number of vehicles occupying a unit section of the road at any given time. Since it is difficult to locate every vehicle at a particular instant using the model the following method which uses the principle of conservation of vehicles is used.

Three traps namely A, B, C are selected on the road as shown in the Figure 4.2. Now the number of vehicles leaving each of the traps in a time interval say, 'x' seconds, are noted.

```
            |============|============|

    -------->Direction 1               |

            |                    <-----------Direction 2

            |============|============|=

            A            B            C
```

Fig 4.2 Bidirectional Single Lane Road

Let the number of vehicles leaving each trap in this same interval be N(A), N(B) and N(C) respectively, in direction 1. As what ever flow gets in has to get out, We can say that in the time interval 'x' seconds N(B)–N(A) vehicles are present in direction 1 in section A–B, N(B)–N(C) are present in direction 1 in section B–C. Similarly in the same time interval 'x' seconds N(C)' N(B)' N(A)' leave traps C, B, and A in direction 2. The density (or its surrogate measurement) can now be defined for trap A–B, B–C and for the whole section A–C (in the time interval x seconds) as follows.

$$\text{Density}_{A\text{-}B} = (N(A) - N(B)) + (N(B)' - N(C)')$$

$$\text{Density}_{B\text{-}C} = (N(B)\text{-}N(C)) + (N(C)'\text{-}N(B)')$$

$$\text{Density}_{A\text{-}C} = (N(A)\text{-}N(C)) + (N(C)'\text{-}N(A)')$$

The process is repeated for each time interval for a total of an hour. The time interval is selected on the basis of the average speed of the stream. A sample calculation is presented to illustrate this idea below.

4.3.3 Implementation of the methodology using the Simulation Model

4.3.3.1 Speed–Throughput–Density Relationships for all Maruti Stream

A road file corresponding to the ideal conditions mentioned in section 4.3.2.1 is prepared. This road file is used for all the computation purposes. For studying the capacity of all Maruti Car stream the flow (or demand) is varied form 6

veh/hr (also equal to PCE/hour) to 1230 veh/hr (combined in both directions). At each flow level the average speed of the stream, the density and throughput of the stream are calculated using result processing programs. Table 4.1 shows the results obtained.

Graphs depicting the variation of speed-throughput and speed-density are shown in Fig 4.3 and 4.4. The speed-throughput relationship shows a linear pattern with a not too steep slope upto capacity, there after the slope appears to be steep indicating that throughput decreases at a more rapid rate in unstable flow conditions compared to stable flow conditions. The speed-density relation indicates that density increases more rapidly near capacity than at the free flowing conditions.

As mentioned earlier capacity is taken as the flow corresponding to maximum throughput. Working back from speed-density relationship the flow corresponding to maximum throughput (assuming that the maximum throughput is 53131 Veh-Km/Hr) the capacity of a single lane road under ideal conditions can approximately be taken as 1070 Maruti cars per hour. The level-of-service has been calibrated using speed and density as the criteria. This is shown in Table 4.2.

Table 4.1 Speed–Throughput–Density relationships of all Maruti Car stream

Demand (Veh/Hr)	Speed statistics (Km/Hr)		Throughput (Veh-Km/Hr)	Density (Veh/Km)	
	Mean	std.dev		Mean	std.dev
6	65.60	1.30	302	0.08	0.01
14	64.00	2.10	707	0.22	0.10
35	63.60	3.00	1931	0.56	0.20
104	63.00	3.90	5068	1.54	0.48
208	62.50	4.10	10255	3.19	0.83
316	62.40	4.40	15597	4.84	1.50
354	62.15	4.70	17968	5.65	1.65
470	61.63	5.10	24403	7.18	1.78
551	61.27	5.60	30761	8.73	1.91
600	60.66	6.00	32891	9.93	2.06
725	60.05	6.19	35710	11.84	2.37
843	59.83	6.70	40973	14.04	4.45
901	59.30	6.92	43008	15.70	4.90
1010	58.80	7.10	49020	17.10	5.39
1078	58.36	7.50	53131	18.27	6.19
1096	57.30	7.52	52437	18.97	7.01
1230	54.80	7.70	50657	21.40	7.20

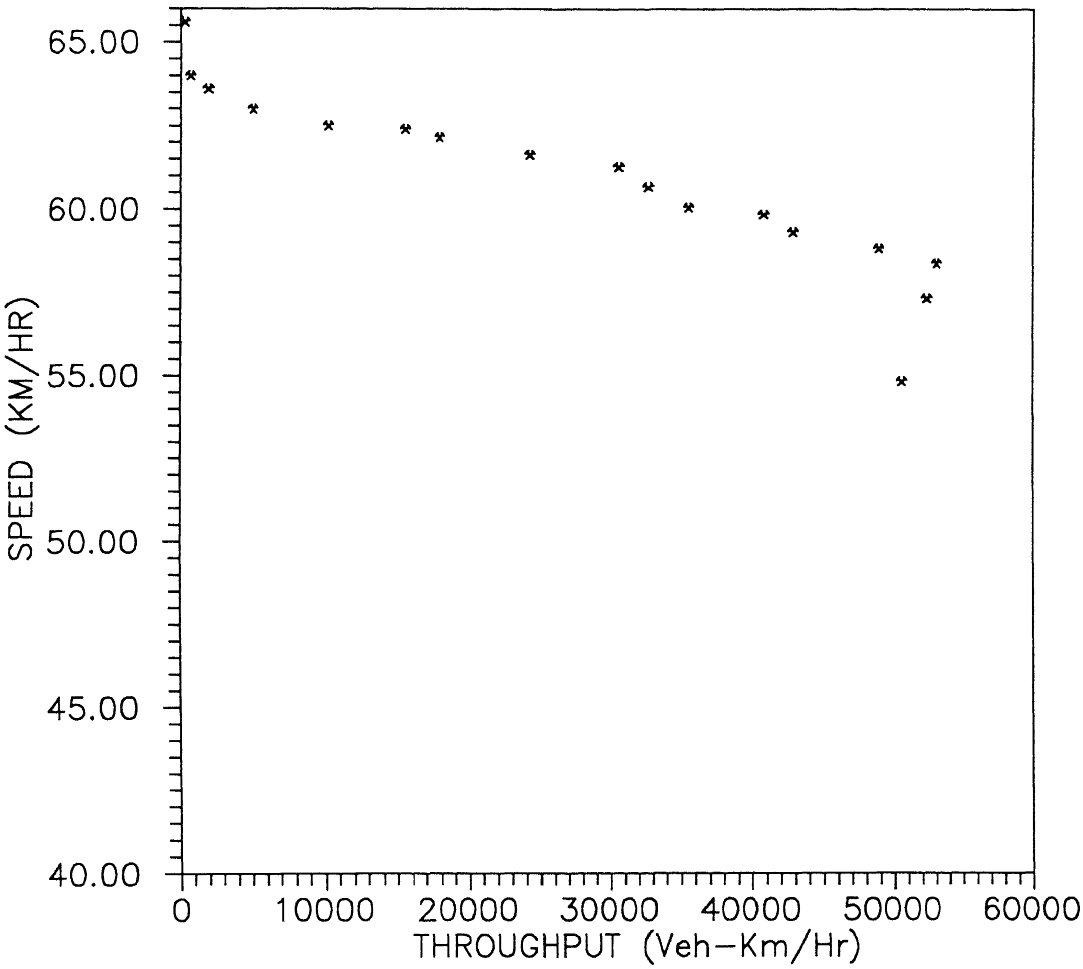


Fig 4.3 Speed-Throughput Variation for all Maruti Car Stream

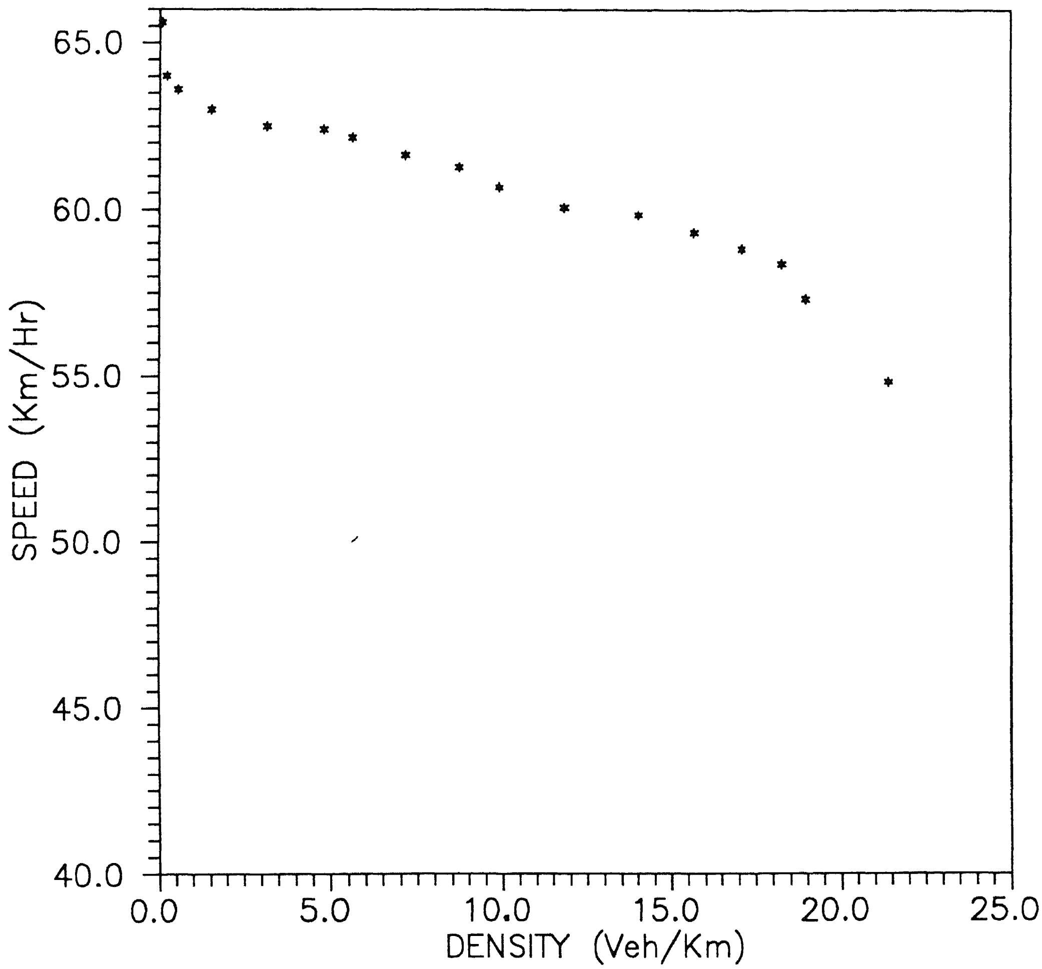


Fig 4.4 Speed-Density Variation for all Maruti Car Stream

Table 4.2 Speed and density values at various operating conditions of For All Maruti Car stream

Level-of-service	Speed (Km/Hr)	Density (PCE/Km)
A	≥ 62.86	≤ 2.0
B	61.60 - 62.86	2.0 - 6.0
C	61.27 - 61.60	6.0 - 9.0
D	59.83 - 61.27	9.0 - 14.0
E	58.36 - 59.83	14.0 - 18.0
F	≤58.36	≥18.00

The effect on speed-throughput-density relationships of all Maruti stream due to each incremental addition of truck bus and tractor is discussed in the following section.

4.3.3.2 Speed–Throughput–Density Relationships for Maruti–Truck, Maruti–Bus and Maruti–Tractor Streams

For studying the above effect trucks are introduced in the all Maruti Car stream by replacing Maruti Cars by 10 percent trucks. For this composition (90% Maruti Cars, 10% trucks), speed-throughput density relationships are studied. The proportion of trucks is now increased in steps of 10% until all the Maruti Cars are replaced by trucks. At each step the flow is varied from 200 veh/hr to 1100 veh/hr combined in both directions. At each flow level speed, throughput and density are noted. The results are presented from Table 4.3 to 4.12.

The same procedure is repeated for bus and tractor. The results are presented in tables 4.13 to 4.22 for bus and in Tables 4.23 to 4.32 for tractor respectively.

Graphs are plotted with speed as ordinate as throughput as abscissa for all the results. These are presented in Fig 4.5 to 4.7. Fig 4.5 and 4.6 indicate that behavior of truck and bus follow more or less similar pattern when they are interacting with Maruti Car. It can be observed from these figures that the speed drop becomes more pronounced as the proportion of the truck increases, resulting in steeper curves. We know that the theoretical speed-flow curve follows a parabolic variation. But it need not always be true. The behavior of the stream in free flow condition and forced flow condition need not be the same. Keeping this and the overall nature of curves in the view , they are approximated by asymmetrical parabolas. These are shown in Figures 4.9 to 4.12.

For fitting these curves it is assumed that the parabola is uniquely determined by x, y and h as shown in Figure 4.8. A range of parabolas were generated using these as variables and the parabola with least error is assumed to be the best fit.

From the graphs one can observe that the speed throughput curve tend to become theoretical parabola when the proportion of trucks in the stream become around 70 %. The same pattern can be observed for bus also. When tractors are introduced the speed drop seems to be exponential as can be seen from Figure 4.7. Hence, exponential curves of the form $y = a\,e^{bx}$ are fitted for tractors. This is presented in Figure 4.13. The characteristics of the curves are presented in Tables 4.33 to 4.35.

Table 4.3 Speed–Throughput –Density results for 10 % Truck in all Maruti stream

Demand (Veh/Hr)	Speed (Km/Hr) of stream		Density (Veh/Km) of the stream		Throughput (Veh-Km/Hr) of the stream
	Mean	std.dev	Mean	std.dev	
208	61.6	5.00	3.24	0.82	10161
316	59.3	5.30	5.96	1.60	17612
551	58.5	6.12	9.05	1.61	28722
725	54.2	7.00	13.57	3.17	32464
901	49.3	7.12	17.10	5.26	36942
1096	40.2	8.00	25.30	6.14	34726

Table 4.4 Speed –Throughput –Density results for 20 % Truck in all Maruti stream

Demand (Veh/Hr)	Speed (Km/Hr) of the stream		Density (Veh/Km) of the stream		Throughput (Veh-Km/Hr) of the stream
	Mean	std.dev	Mean	std.dev	
208	60.1	5.60	3.34	0.85	9896
316	58.9	5.80	6.21	1.60	16637
551	55.0	5.90	9.43	1.61	25859
725	50.9	6.20	14.02	2.52	29033
901	43.5	7.50	20.14	7.96	32898
1096	34.5	10.70	34.66	8.14	32753

Table 4.5 Speed –Throughput–Density results for 30 % Truck in all Maruti stream

Demand (Veh/Hr)	speed (Km/Hr) of stream		Density (Veh/Km) of stream		Throughput (Veh-Km/Hr) of the stream
	Mean	std.dev	Mean	std.dev	
208	58.50	6.20	3.37	0.83	9561
316	56.20	5.40	6.36	1.88	16288
551	52.10	5.60	9.76	1.98	24239
725	48.20	4.80	15.20	2.40	26649
901	38.90	9.10	21.50	7.50	29538
1096	33.10	9.20	36.02	7.90	27584

Table 4.6 Speed –Throughput –Density results for 40 % Truck in all Maruti stream

Demand (Veh/Hr)	speed (Km/Hr) of stream Mean	std.dev	Density (Veh/Km) of stream Mean	std.dev	Throughput (Veh-Km/Hr) of the stream
208	57.30	5.00	3.47	0.89	9299
316	54.20	5.30	6.87	1.72	15503
551	50.00	6.12	10.32	1.82	23660
725	45.20	7.00	16.32	2.43	24628
901	36.90	7.12	23.29	6.14	26436
1096	32.00	8.00	36.49	8.81	26008

Table 4.7 Speed –Throughput –Density results for 50 % Truck in all Maruti stream

Demand (Veh/Hr)	speed (Km/Hr) of stream Mean	std.dev	Density (Veh/Km) of stream Mean	std.dev	Throughput (Veh-Km/Hr) of the stream
208	55.80	6.40	3.50	0.94	8977
316	50.50	5.10	6.94	1.77	14703
551	47.10	5.40	11.03	1.56	22349
725	42.70	3.30	17.26	2.25	23807
901	36.40	6.90	24.60	6.80	25286
1096	31.80	7.40	37.20	7.20	24996

Table 4.8 Speed –Throughput –Density results For 60 % Truck in all Maruti stream

Demand (Veh/Hr)	speed (Km/Hr) of stream Mean	std.dev	Density (Veh/Km) of stream Mean	std.dev	Throughput (Veh-Km/Hr) of the stream
208	53.50	7.00	3.57	0.97	8627
316	50.00	4.90	7.12	1.87	14238
551	45.15	4.80	11.37	1.77	21766
725	41.60	3.40	17.75	2.54	22891
901	36.00	6.90	25.83	7.70	25621
1096	30.80	7.10	38.40	7.81	24232

Table 4.9 Speed –Throughput –Density results for 70 % Truck in all Maruti stream

Demand (Veh/Hr)	speed (Km/Hr) of stream Mean	std.dev	Density (Veh/Km) of stream Mean	std.dev	Throughput (Veh-Km/Hr) of the stream
208	51.70	6.50	3.78	0.96	8396
316	47.70	4.50	7.12	1.68	13565
551	43.20	4.40	12.23	1.87	21335
725	39.10	3.50	18.62	2.54	22319
901	35.10	6.20	26.00	7.00	25276
1096	30.10	6.90	39.40	7.20	23336

Table 4.10 Speed –Throughput –Density results for 80 % Truck in all Maruti stream

Demand (Veh/Hr)	speed (Km/Hr) of stream Mean	std.dev	Density (Veh/Km) of stream Mean	std.dev	Throughput (Veh-Km/Hr) of the stream
208	50.50	6.00	3.90	1.002	8203
316	46.10	3.20	7.62	1.690	13147
551	42.01	3.00	12.80	1.790	20150
725	38.80	2.80	18.85	2.730	22043
901	34.40	5.80	26.17	6.430	25190
1096	29.50	6.00	40.90	7.400	22661

Table 4.11 Speed –Throughput –Density results for 90 % Truck in all Maruti stream

Demand (Veh/Hr)	speed (Km/Hr) of stream Mean	std.dev	Density (Veh/Km) of stream Mean	std.dev	Throughput (Veh-Km/Hr) of the stream
208	49.50	4.50	3.97	1.04	8604
316	44.10	2.50	7.80	1.79	13017
551	40.05	2.10	13.19	1.89	20238
725	37.60	2.90	19.23	4.16	22070
901	33.80	5.90	28.10	7.12	23893
1096	28.60	5.80	42.30	7.20	23500

Table 4.12 Speed –Throughput –Density results for 100 % Truck in all Maruti stream

Demand (Veh/Hr)	speed (Km/Hr) of stream		Density (Veh/Km) of stream		Throughput (Veh-Km/Hr) of the stream
	Mean	std.dev	Mean	std.dev	
208	48.00	2.60	4.01	1.05	7556
316	43.00	2.10	8.00	1.90	12480
551	39.10	2.00	13.32	2.00	18944
725	35.10	4.30	21.90	6.55	20523
901	33.10	6.20	29.88	8.56	22930
1096	26.00	6.00	44.10	7.10	20891

Table 4.13 Speed –Throughput –Density results for 10 % Busses in all Maruti stream

Demand (Veh/Hr)	speed (Km/Hr) of stream		Density (Veh/Km) of stream		Throughput (Veh-Km/Hr) of the stream
	Mean	std.dev	Mean	std.dev	
208	61.90	3.90	3.22	0.82	10192
316	60.50	4.10	5.84	1.59	17790
551	58.60	3.90	8.90	1.66	29296
725	56.80	4.80	12.91	3.50	33307
901	49.98	5.90	16.20	3.60	37398
1096	42.36	7.00	23.40	6.53	36235

Table 4.14 Speed –Throughput–Density results for 20 % Busses in all Maruti stream

Demand (Veh/Hr)	speed (Km/Hr) of stream		Density (Veh/Km) of stream		Throughput (Veh-Km/Hr) of the stream
	Mean	std.dev	Mean	std.dev	
208	60.90	5.00	3.30	0.85	10031
316	58.80	5.30	5.99	1.54	17052
551	56.00	6.12	9.22	1.49	27965
725	52.60	7.00	13.61	2.53	31047
901	46.10	7.12	14.87	3.12	35281
1096	38.60	8.00	32.22	6.53	33376

Table 4.15 Speed –Throughput –Density results for 30 % Busses in all Maruti stream

Demand (Veh/Hr)	speed (Km/Hr) of stream Mean	std.dev	Density (Veh/Km) of stream Mean	std.dev	Throughput (Veh-Km/Hr) of the stream
208	59.80	4.80	3.3	0.91	9846
316	56.80	5.10	6.17	1.60	16464
551	53.80	4.90	9.82	1.70	25422
725	49.60	5.70	14.20	2.72	27519
901	41.00	9.00	19.60	4.20	30808
1096	33.90	9.40	35.30	7.20	28808

Table 4.16 Speed –Throughput –Density results for 40 % Busses in all Maruti stream

Demand (Veh/Hr)	speed (Km/Hr) of stream Mean	std.dev	Density (Veh/Km) of stream Mean	std.dev	Throughput (Veh-Km/Hr) of the stream
208	58.80	4.80	3.47	0.90	9689
316	55.70	5.30	6.42	1.65	16119
551	51.50	4.80	9.89	1.71	24807
725	46.50	4.90	15.47	3.25	26312
901	38.80	8.90	22.80	6.09	27909
1096	34.13	8.80	36.00	8.00	26850

Table 4.17 Speed –Throughput –Density results for 50 % Busses in all Maruti stream

Demand (Veh/Hr)	speed (Km/Hr) of stream Mean	std.dev	Density (Veh/Km) of stream Mean	std.dev	Throughput (Veh-Km/Hr) of the stream
208	57.60	4.90	3.50	0.89	9494
316	53.70	5.20	6.60	1.52	15589
551	48.60	4.50	10.64	1.50	23482
725	42.30	5.00	17.13	3.20	25815
901	35.70	8.80	23.70	8.00	26863
1096	32.00	7.20	36.40	7.00	26299

Table 4.18 Speed –Throughput –Density results for 60 % Busses in all Maruti stream

Table 4.18 Speed –Throughput –Density results for 60 % Busses in all Maruti stream

Demand (Veh/Hr)	speed (Km/Hr) of stream Mean	std.dev	Density (Veh/Km) of stream Mean	std.dev	Throughput (Veh-Km/Hr) of the stream
208	56.50	4.90	3.55	0.92	9299
316	51.40	5.20	6.87	2.01	14591
551	45.80	4.40	11.00	1.88	22922
725	36.10	7.60	18.31	5.60	24594
901	34.90	8.80	27.19	9.33	26224
1096	30.90	7.00	37.40	7.50	26002

Table 4.19 Speed –Throughput –Density results for 70 % Busses in all Maruti stream

Demand (Veh/Hr)	speed (Km/Hr) of stream Mean	std.dev	Density (Veh/Km) of stream Mean	std.dev	Throughput (Veh-Km/Hr) of the stream
208	54.90	4.50	3.62	0.94	9023
316	48.70	4.90	7.31	1.36	14514
551	43.50	3.90	12.48	1.68	21941
725	36.00	3.93	19.43	2.51	23188
901	33.46	5.60	28.10	7.60	26161
1096	30.60	6.50	39.20	7.00	25464

Table 4.20 Speed –Throughput –Density results for 80 % Busses in all Maruti stream

Demand (Veh/Hr)	speed (Km/Hr) of stream Mean	std.dev	Density (Veh/Km) of stream Mean	std.dev	Throughput (Veh-Km/Hr) of the stream
208	53.80	4.40	3.69	0.90	8851
316	47.20	4.50	7.36	1.75	13658
551	41.30	3.50	12.85	1.95	21069
725	34.20	4.00	21.40	2.54	22601
901	33.10	4.40	29.20	5.84	25299
1096	30.00	5.50	40.01	7.00	25120

Table 4.21 Speed –Throughput–Density results for 90 % Busses in all Maruti stream

Demand (Veh/Hr)	speed (Km/Hr) of stream Mean	std.dev	Density (Veh/Km) of stream Mean	std.dev	Throughput (Veh-Km/Hr) of the stream
208	52.20	4.40	3.75	0.97	8604
316	45.00	4.50	7.67	1.80	13017
551	38.80	3.50	13.44	1.88	20238
725	33.80	4.00	22.10	2.56	22070
901	30.50	4.40	31.20	6.72	23893
1096	29.00	5.50	41.60	7.10	23500

Table 4.22 Speed –Throughput –Density results for 100 % Busses in all Maruti stream

Demand (Veh/Hr)	speed (Km/Hr) of stream Mean	std.dev	Density (Veh/Km) of stream Mean	std.dev	Throughput (Veh-Km/Hr) of the stream
208	50.80	3.40	3.90	1.06	8366
316	43.30	3.20	8.04	1.96	12509
551	36.30	1.70	14.11	1.79	19593
725	32.30	2.60	26.50	5.60	21616
901	30.30	6.40	32.62	10.27	23374
1096	27.70	6.10	43.85	11.74	22900

Table 4.23 Speed –Throughput –Density results for 10 % Tractors in all Maruti stream

Demand (Veh/Hr)	speed (Km/Hr) of stream Mean	std.dev	Density (Veh/Km) of stream Mean	std.dev	Throughput (Veh-Km/Hr) of the stream
208	58.6	9.50	3.49	0.91	9650
316	44.3	11.9	8.19	2.67	12828
551	33.6	9.60	16.05	3.70	15988
725	28.2	5.50	18.10	6.01	16669
901	22.9	3.20	30.60	9.71	18897
1096	20.1	2.10	44.10	10.70	17650

Table 4.24 Speed –Throughput –Density results for 20 % Tractors in all Maruti stream

Demand (Veh/Hr)	speed (Km/Hr) of stream Mean	std.dev	Density (Veh/Km) of stream Mean	std.dev	Throughput (Veh-Km/Hr) of the stream
208	51.6	13.7	4.26	1.06	8487
316	33.9	8.60	10.99	3.00	9829
551	27.3	4.60	18.56	3.40	12720
725	24.6	4.00	26.10	6.21	14565
901	21.6	3.80	39.14	10.05	16512
1096	19.7	3.45	50.10	10.90	15670

Table 4.25 Speed –Throughput–Density results for 30 % Tractors in all Maruti stream

Demand (Veh/Hr)	speed (Km/Hr) of stream Mean	std.dev	Density (Veh/Km) of stream Mean	std.dev	Throughput (Veh-Km/Hr) of the stream
208	45.50	14.50	4.94	1.40	7496
316	29.50	6.50	12.07	2.99	8456
551	25.30	3.40	19.62	2.76	11755
725	22.90	3.80	28.61	3.40	13470
901	21.00	3.00	40.10	8.60	15370
1096	19.50	2.80	53.10	9.90	14590

Table 4.26 Speed –Throughput –Density results f or 40 % Tractors in all Maruti stream

Demand (Veh/Hr)	speed (Km/Hr) of stream Mean	std.dev	Density (Veh/Km) of stream Mean	std.dev	Throughput (Veh-Km/Hr) of the stream
208	44.30	15.30	5.04	1.39	7311
316	28.90	6.10	13.10	3.00	8337
551	23.90	2.90	21.22	3.12	11296
725	22.10	2.70	32.62	5.67	13112
901	20.90	2.60	41.02	9.65	15087
1096	19.30	2.40	54.21	10.61	14120

Table 4.27 Speed –Throughput –Density results for 50 % Tractors in all Maruti stream

Demand (Veh/Hr)	speed (Km/Hr) of stream Mean	std.dev	Density (Veh/Km) of stream Mean	std.dev	Throughput (Veh-Km/Hr) of the stream
208	39.60	15.20	5.50	1.57	6528
316	27.40	6.20	13.41	2.66	7986
551	23.10	2.40	21.84	3.41	10997
725	21.50	2.20	32.36	5.54	12708
901	19.90	2.10	43.01	9.51	14692
1096	19.20	1.90	55.10	10.70	14010

Table 4.28 Speed –Throughput –Density results for 60 % Tractors in all Maruti stream

Demand (Veh/Hr)	speed (Km/Hr) of stream Mean	std.dev	Density (Veh/Km) of stream Mean	std.dev	Throughput (Veh-Km/Hr) of the stream
208	35.40	13.90	6.20	1.80	5832
316	25.65	5.80	14.01	2.90	7334
551	22.00	2.90	22.01	3.50	10837
725	20.40	2.50	34.28	5.32	12064
901	19.40	2.40	45.05	7.21	14224
1096	19.00	2.00	56.40	9.10	13934

Table 4.29 Speed –Throughput –Density results for 70 % Tractors in all Maruti stream

Demand (Veh/Hr)	speed (Km/Hr) of stream Mean	std.dev	Density (Veh/Km) of stream Mean	std.dev	Throughput (Veh-Km/Hr) of the stream
208	31.10	11.40	6.20	1.80	5119
316	24.90	5.00	14.22	3.31	6949
551	21.60	1.70	22.90	3.60	10358
725	20.10	1.60	34.58	5.27	11864
901	19.00	2.00	47.30	10.12	14095
1096	18.80	1.40	57.40	10.50	13480

Table 4.30 Speed –Throughput –Density results for 80 % Tractors in all Maruti stream

Demand (Veh/Hr)	speed (Km/Hr) of stream Mean	std.dev	Density (Veh/Km) of stream Mean	std.dev	Throughput (Veh-Km/Hr) of the stream
208	26.70	10.10	7.58	2.00	4619
316	23.00	3.40	15.02	3.27	6640
551	21.20	1.60	23.50	3.80	10211
725	19.90	1.50	35.65	6.95	11670
901	18.90	1.90	49.60	13.34	13931
1096	18.62	1.70	58.00	13.61	13320

Table 4.31 Speed –Throughput –Density results For 90 % Tractors in all Maruti stream

Demand (Veh/Hr)	speed (Km/Hr) of stream Mean	std.dev	Density (Veh/Km) of stream Mean	std.dev	Throughput (Veh-Km/Hr) of the stream
208	25.60	7.70	7.82	2.14	4219
316	21.70	1.80	15.64	3.26	6283
551	20.60	1.20	24.01	4.94	10026
725	18.90	1.00	37.60	8.90	11337
901	18.40	0.90	50.90	10.10	13405
1096	18.20	0.70	59.20	10.70	13190

Table 4.32 Speed –Throughput –Density results for 100 % Tractors in all Maruti stream

Demand (Veh/Hr)	speed (Km/Hr) of stream Mean	std.dev	Density (Veh/Km) of stream Mean	std.dev	Throughput (Veh-Km/Hr) of the stream
208	23.00	1.90	8.09	2.05	3788
316	21.30	1.60	16.00	3.31	6153
551	20.10	0.80	24.83	3.68	9680
725	18.50	0.90	38.65	10.95	10692
901	18.20	1.00	52.63	8.96	12288
1096	17.90	0.70	60.10	10.10	12010

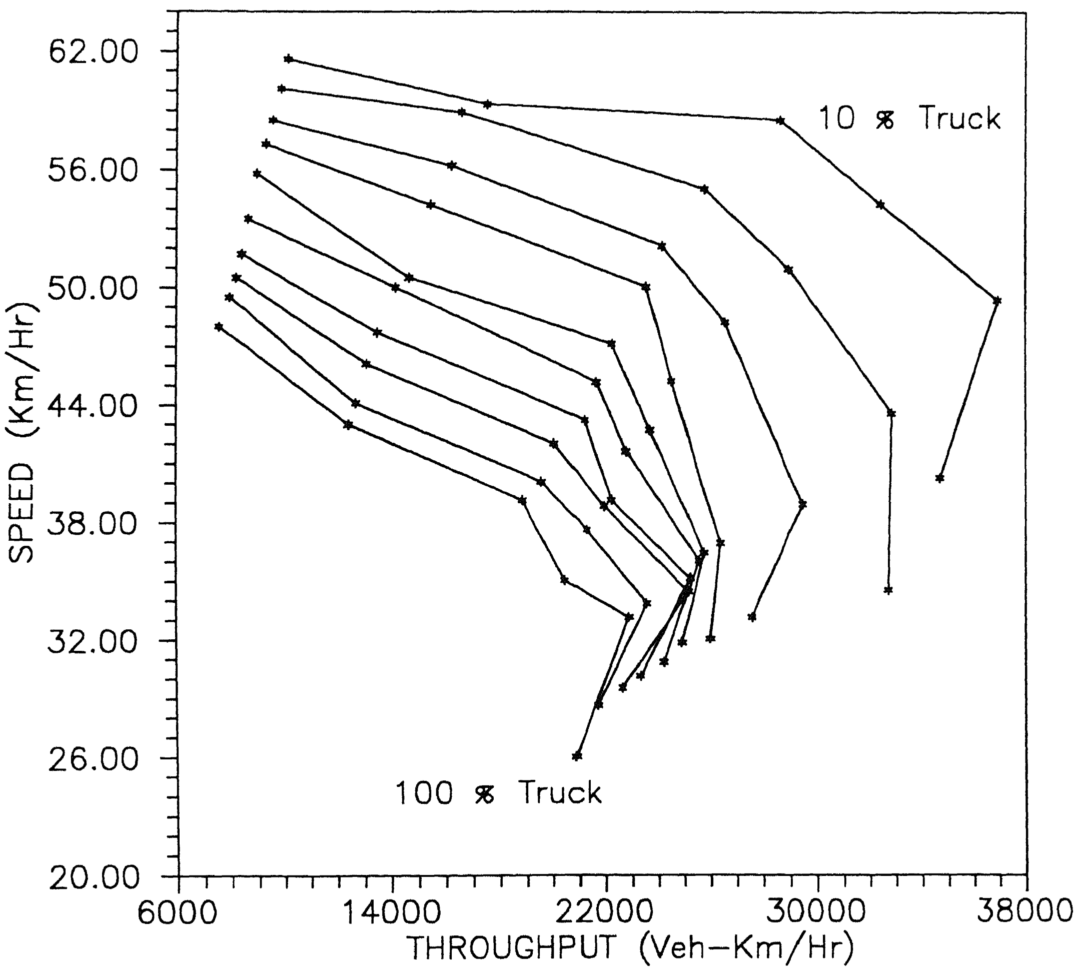


Fig 4.5 Speed-Throughput Variation for Truck-Maruti Car Stream at different % Compositions of Truck

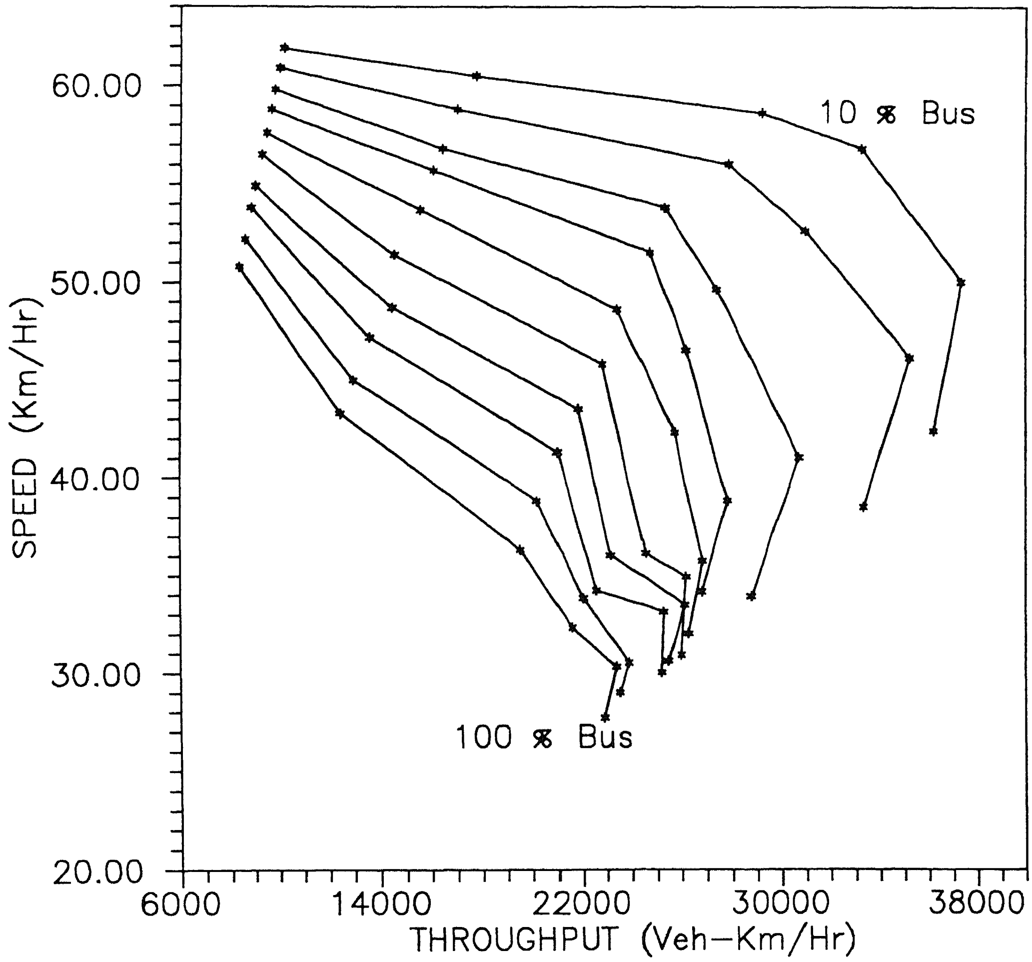


Fig 4.6 Speed-Throughput Variation for Bus-Maruti Car Stream at different % Compositions of Bus

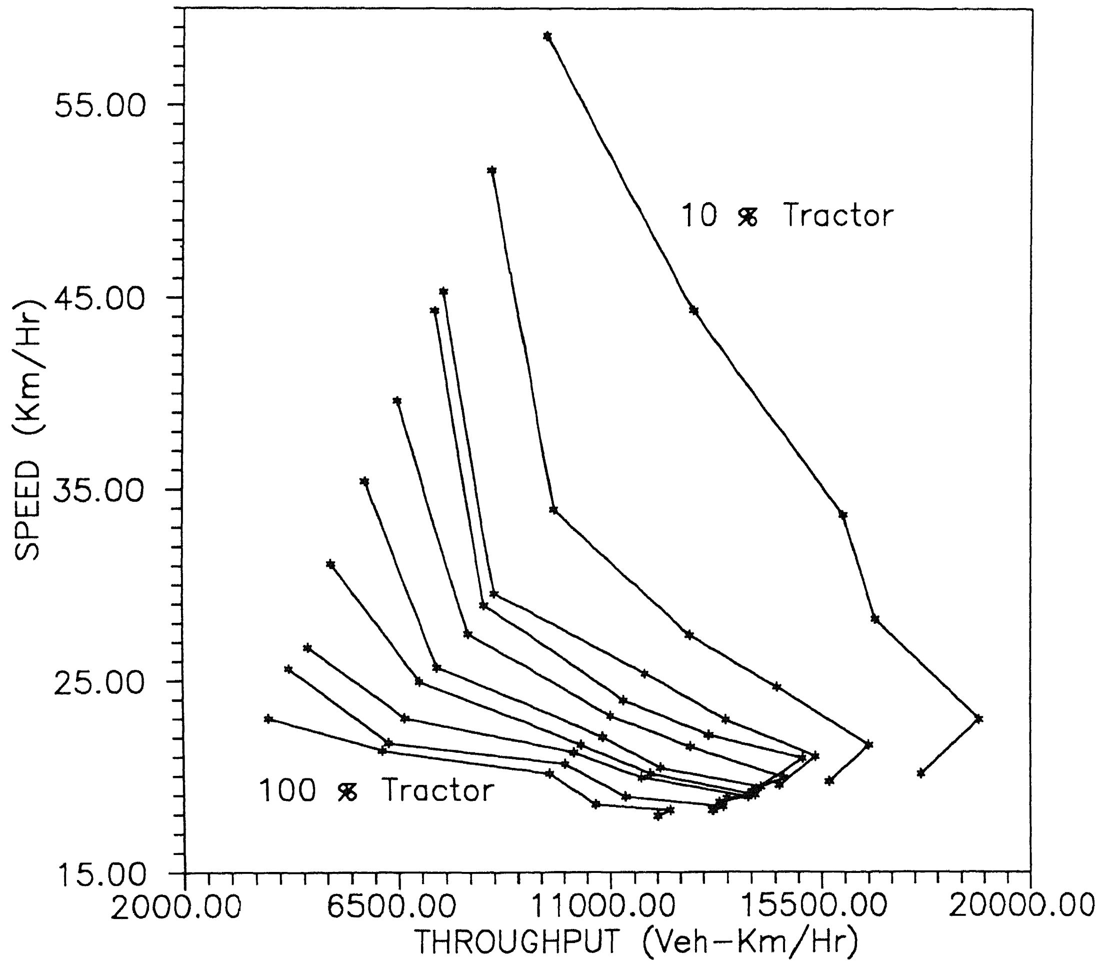


Fig 4.7 Speed-Throughput Variation for Tractor-Maruti Car Stream at different % Compositions of Tractor

Table 4.33 Characteristics of the Asymmetrical Parabola for Truck

% Truck in the stream	Characteristics of the curve		
	X	Y	H
10 %	37000	47.20	1.35
20 %	34300	46.80	1.35
30 %	30400	45.40	1.35
40 %	26500	44.20	1.36
50 %	25500	41.20	1.36
60 %	24900	39.80	1.37
70 %	24600	35.00	1.52
80 %	24300	32.00	1.63
90 %	23800	29.00	1.70
100 %	22900	28.50	1.72

Note : The equation of the parabola is $(y-Y)^2 = -4a(x-X)$

Table 4.34 Characteristics of the Asymmetrical Parabola for Bus

% Bus in the stream	Characteristics of the curve		
	X	Y	H
10 %	37800	48.20	1.35
20 %	36000	47.10	1.35
30 %	31800	45.90	1.35
40 %	29000	44.80	1.36
50 %	27000	42.80	1.36
60 %	26400	40.90	1.37
70 %	26000	36.00	1.50
80 %	25400	33.00	1.60
90 %	24000	30.00	1.65
100 %	23500	29.00	1.65

Note : The equation of the parabola is $(y-Y)^2 = -4a(x-X)$

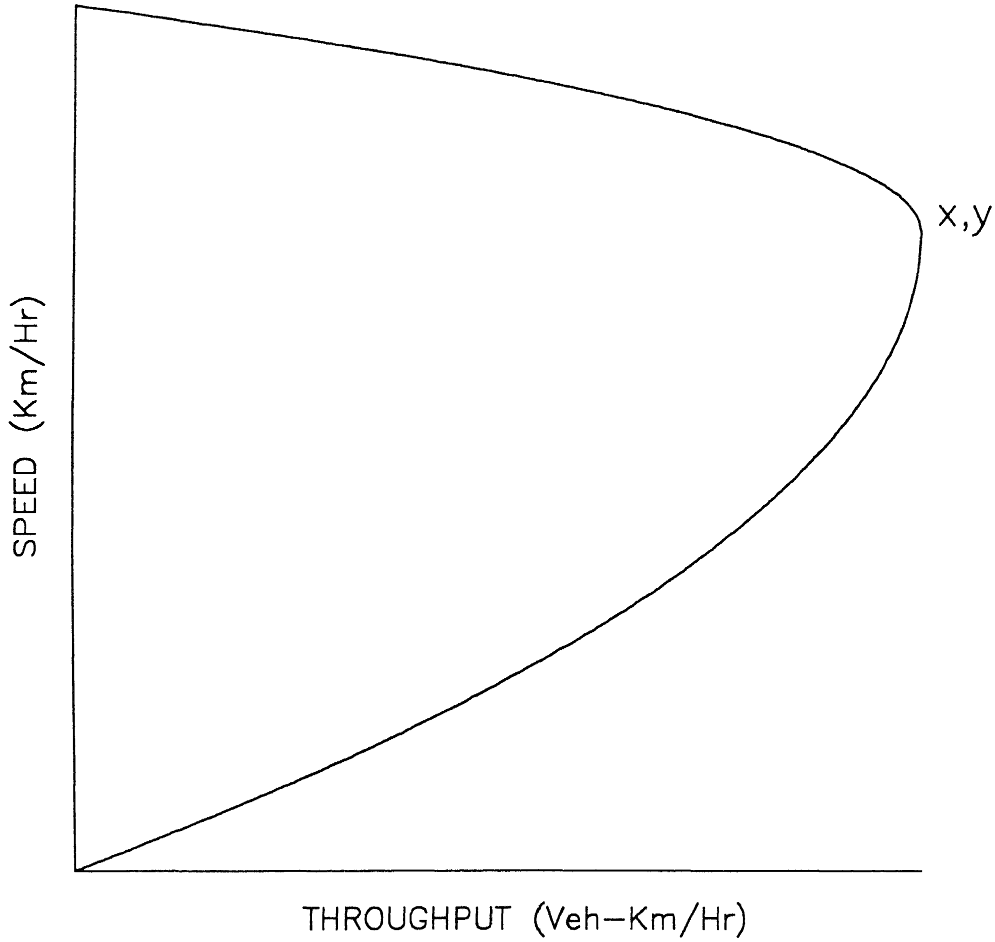


Fig. 4.8 A Hypothetical Asymmetrical Parabola

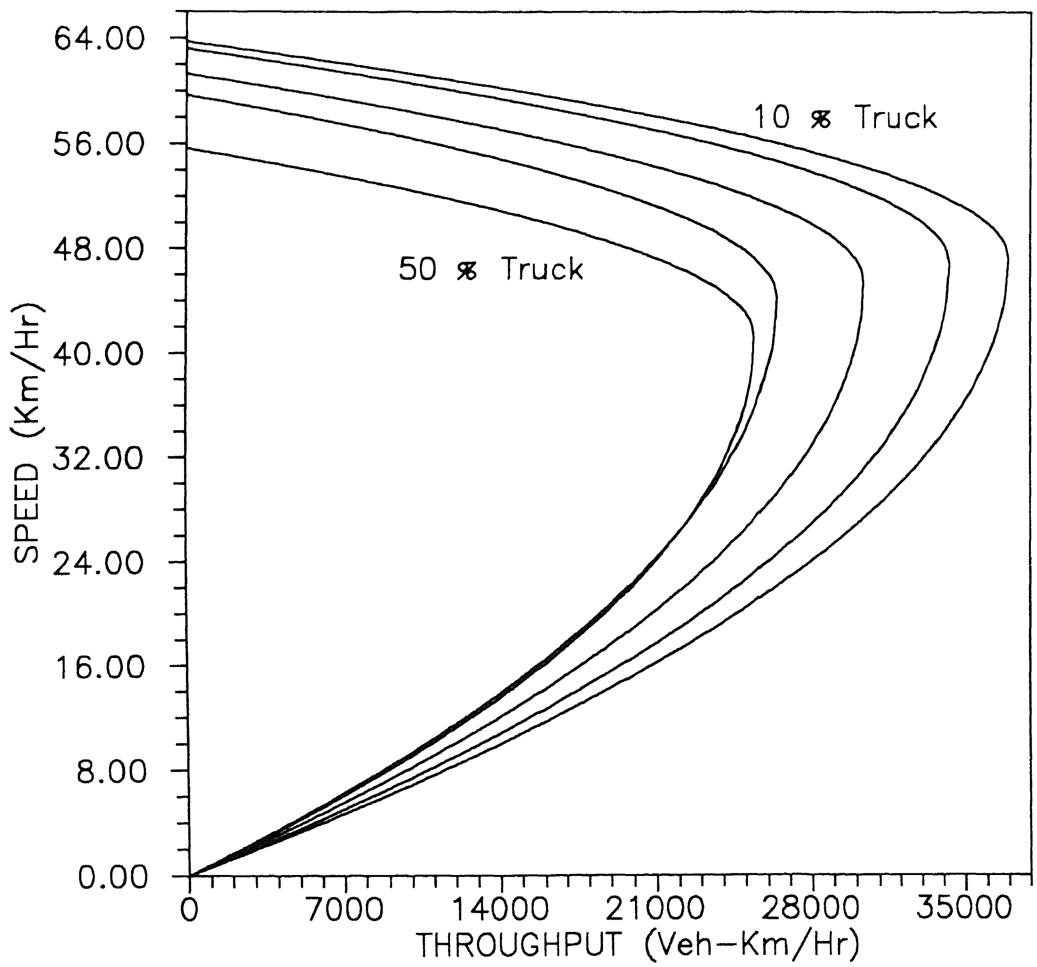


Fig 4.9 Approximated Asymmetrical Parabolic Speed-Throughput Variation for Truck-Maruti Car Stream (Trucks 10 to 50 % in Composition)

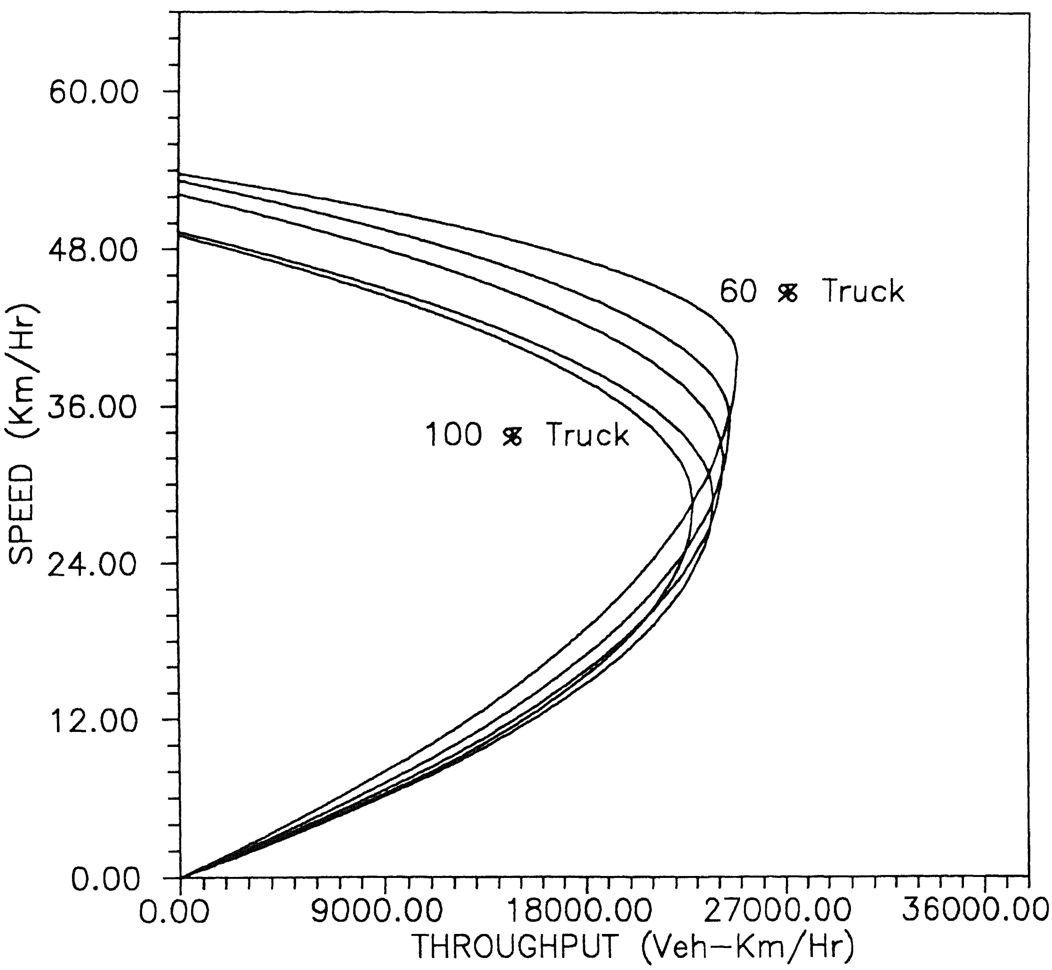


Fig 4.10 Approximated Asymmetrical Parabolic Speed-Throughput Variation for Truck-Maruti Car Stream (Trucks 60 to 100 % in Composition)

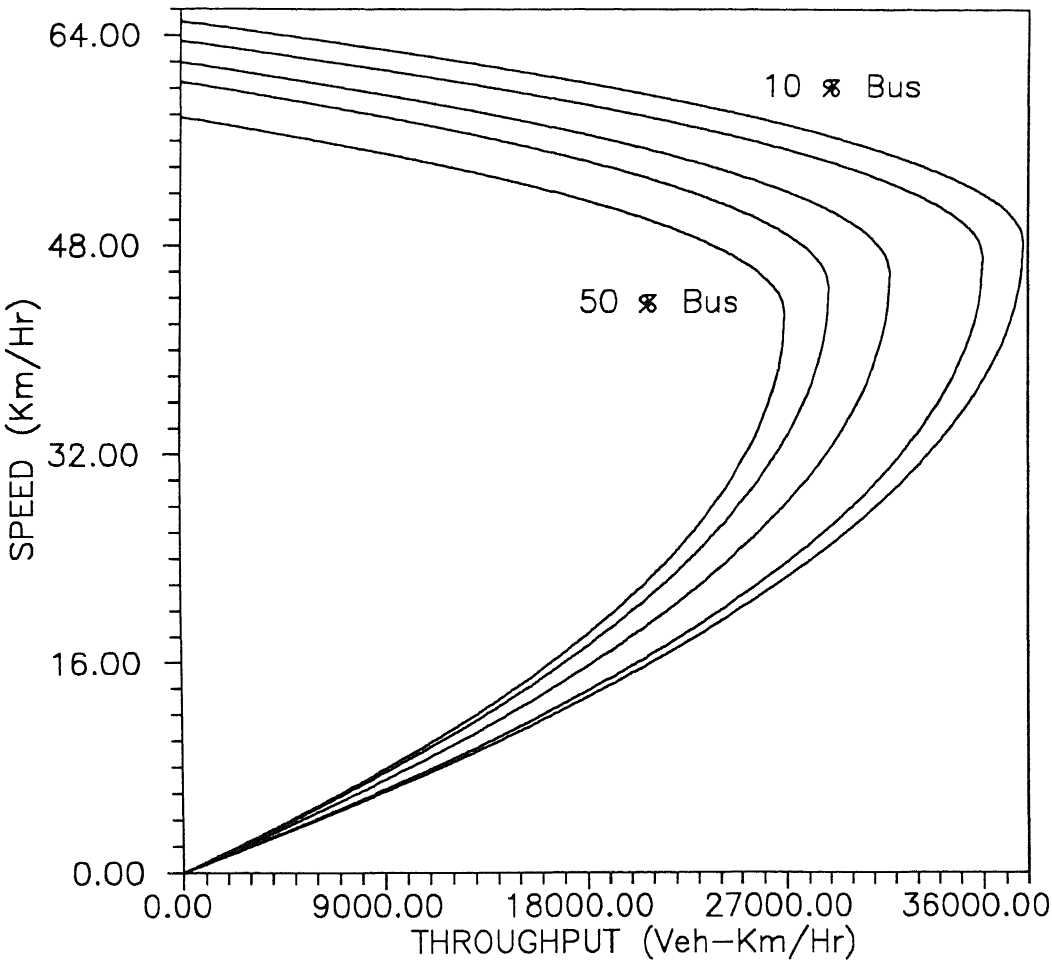


Fig 4.11 Approximated Asymmetrical Parabolic Speed-Throughput Variation for Bus-Maruti Car Stream (Buses 10 to 50 % in Composition)

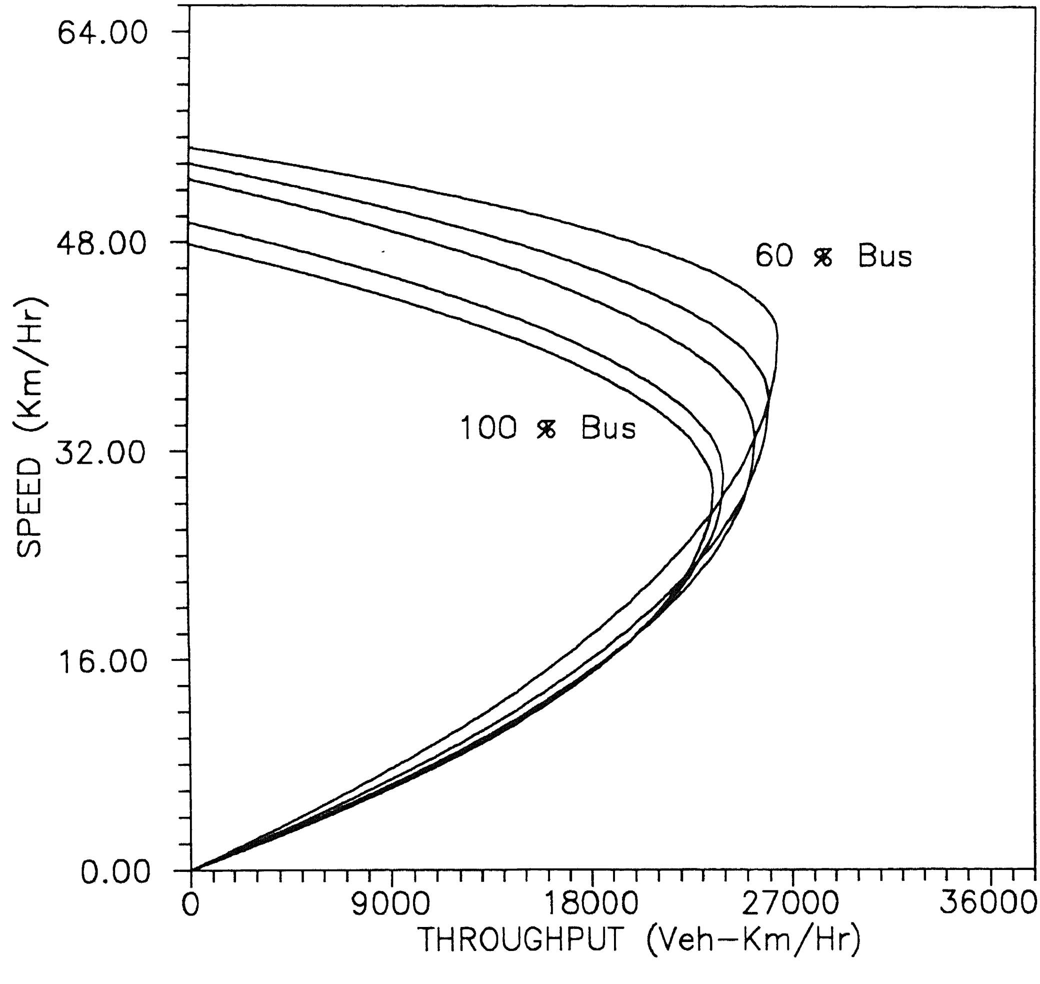


Fig 4.12 Approximated Asymmetrical Parabolic Speed-Throughput Variation for Bus-Maruti Car Stream (Buses 60 to 100 % in Composition)

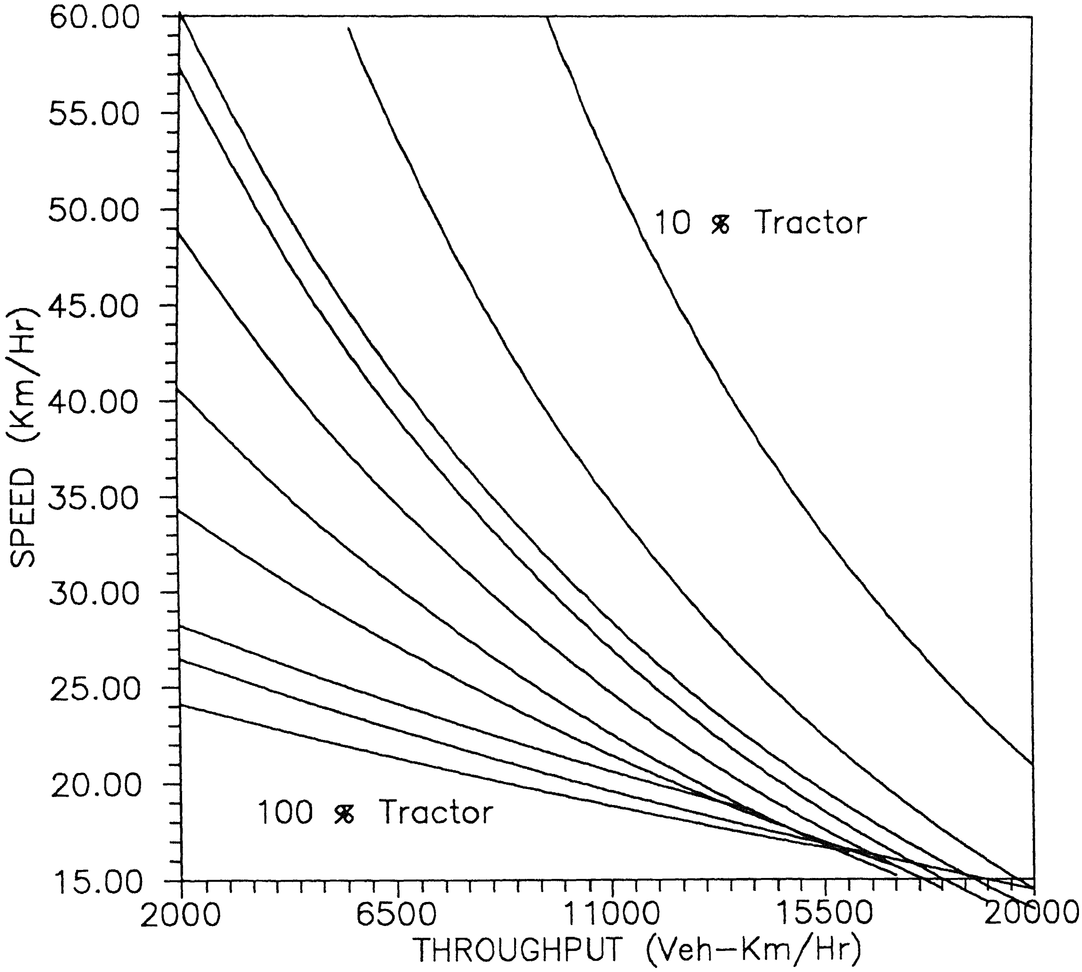


Fig 4.13 Approximated Exponential Speed-Throughput Variation for Tractor-Maruti Car Stream (Tractors 0 to 100 % Composition)

Table 4.35 Characteristics of Exponential distribution Curves for Tractors

% Tractor in the stream	Coefficients of exponential curve a	b (10^{-5})
10	160.5	10.00
20	101.5	9.70
30	71.1	8.30
40	67.8	8.20
50	56.8	7.60
60	46.4	6.60
70	38.2	5.20
80	30.3	3.54
90	28.3	3.51
100	25.5	2.76

In all the above graphs the throughput is expressed as veh-km/hr. Graphs are again plotted converting this throughput into equivalent PCE-km/hr. These are presented in Figs 4.14 to 4.15. The PCE values calculated using the concept of equivalence vehicle throughput are used for this purpose.

The various possible level-of-service conditions when truck, bus and Tractors are introduced in the stream using speed as the sole criteria are given in Tables 4.36 to 4.38.

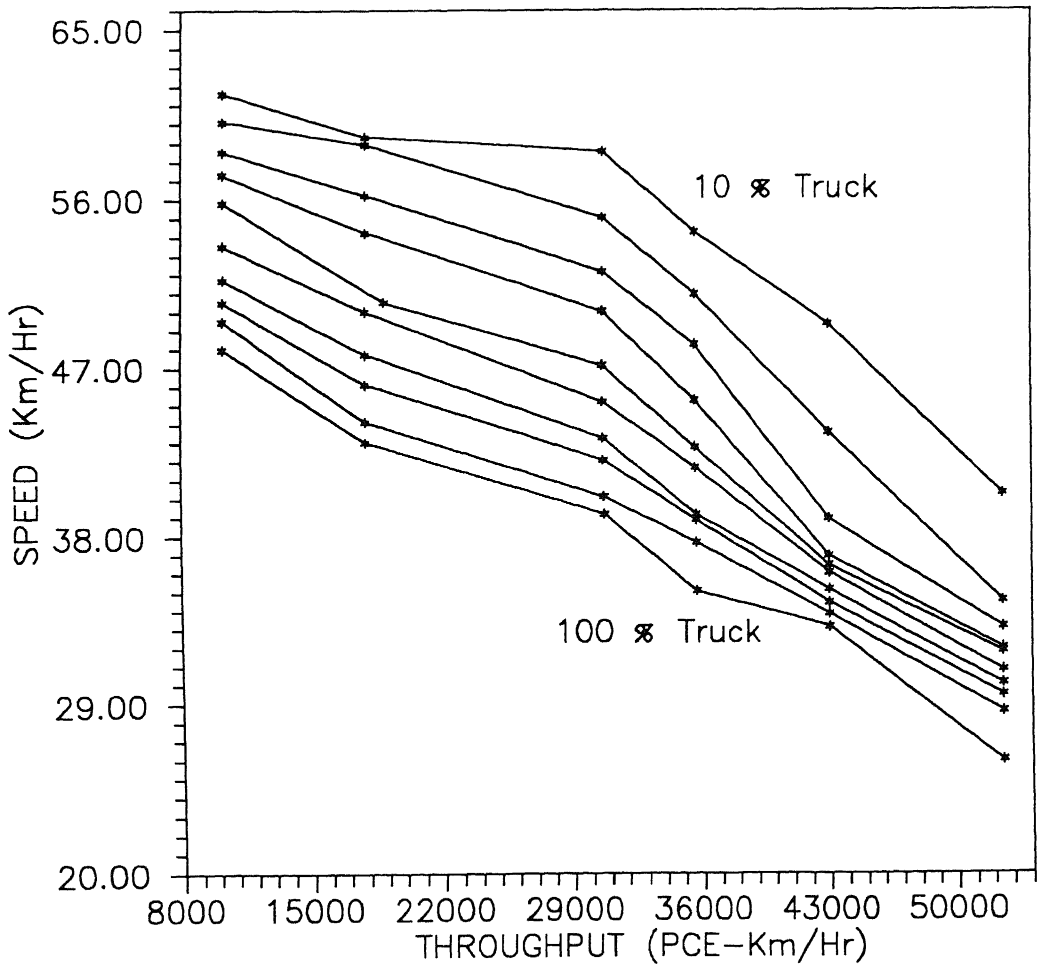


Fig 4.14 Speed-Throughput Variation for Truck Maruti Car Stream at different %' Compositions of Truck

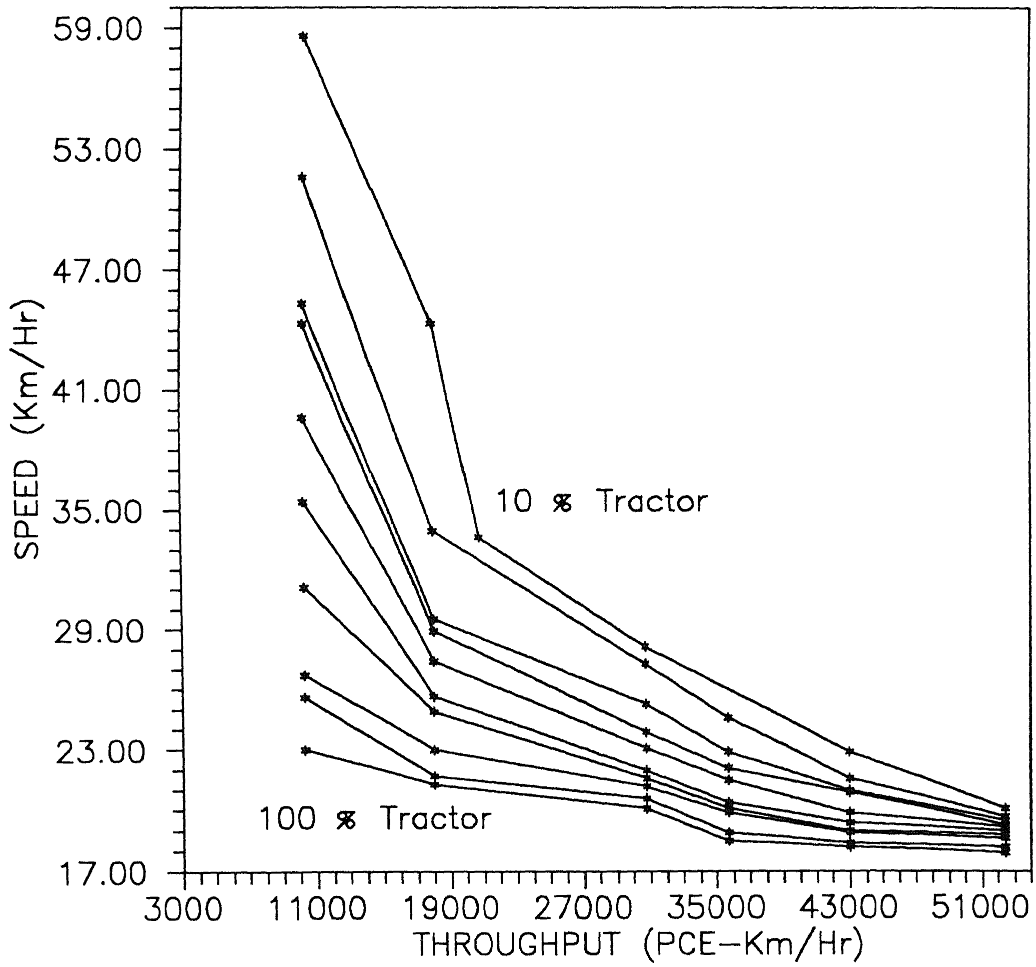


Fig 4.15 Speed-Throughput Variation for Tractor-Maruti Car Stream at different % Compositions of Tractor

Tablc 4.36 Various Available Levels of Service when truck is introduced in all Maruti Car Stream

% Truck in the stream	Available Levels of Service
10 %	B, C, D, E, F
20 %	B, C, D, E, F
30 %	D, E, F
40 %	D, E, F
50 %	Only F from 50 % onwards

Table 4.37 Various Available Levels of Service when Bus is introduced in all Maruti Car Stream

% Bus in the stream	Available Levels of Service
10 %	A, B, C, D, E, F
20 %	B, C, D, E, F
30 %	C, D, E, F
40 %	D, E, F
50 %	E, F
60 %	Only F from 60 % onwards

Table 4.38 Various Available Levels of Service when Tractor is introduced in all Maruti Car Stream

% Tractor in the stream	Available Levels of Service
10 %	D, E, F
20 %	Only F from 20 % onwards

4.3.3.3 Simulation of a Heterogeneous Traffic Stream

In the above study only two types of vehicles haven been considered in the traffic stream, i.e., Maruti Car and either truck or bus or tractor. In general the traffic on Indian roads is highly heterogeneous with traffic composition consisting of vehicles like Bus, LCV, Jeep ,etc., To study the behavior of a mixed traffic stream a traffic stream consisting of following vehicles is taken.

1. 8 % Ambassador Car
2. 3% Premier
3. 20% Maruti Car
4. 8% Jeep
5. 5% Matador Van
6. 10% Bus
7. 35% Truck
8. 1% Tractor

is taken. This composition represents a typical traffic stream on Indian rural roads. The speed-density-throughput characteristics of the stream were studied at flow levels

ranging from 100 veh/hr, combined in both directions to about 1350 veh/hr combined in both directions. These characteristics are presented in Table 4.39

Table 4.39 Speed-Density-Throughput Characteristics for a mixed traffic Stream

Demand (Veh/Hr)	Speed Characteristics Mean (Km/Hr)	Speed Characteristics Std.dev (Km/Hr)	Density Characteristics Mean (Veh/Km)	Density Characteristics Std.dev (Veh/Km)	Throughput of the stream (Veh-Km/Hr)
103	52.7	4.7	1.84	1.10	4237
206	51.8	5.2	3.69	1.45	9261
290	50.0	4.9	5.60	1.70	11241
334	48.7	5.1	6.75	1.90	12881
355	47.6	3.9	7.32	2.12	15023
392	46.8	3.7	8.12	2.50	16749
470	43.1	6.0	10.50	2.75	18637
612	39.0	5.2	15.14	4.60	10026
852	32.7	7.0	25.19	6.00	9536
1385	21.9	6.2	63.40	9.45	8989

Table 4.40 Speed characteristics of individual vehicles in the mixed traffic stream when the demand is 1385 veh/hr

Vehicle Type	Speed (Km/Hr) Characteristics (combined in both directions)	
	Mean	Std.dev
Ambassador	20.9	6.4
Fiat	20.7	5.9
Maruti	22.1	6.2
Jeep	21.3	5.6
Matador	20.3	5.1
Bus	21.8	6.9
LCV	22.2	6.5
Truck	22.3	5.2
Tractor	17.7	3.2

The individual average speeds of the vehicles when the demand is 1385 veh/hr is given in table 4.40. From the table it can be observed that all the vehicles are traveling at approximately same speed at this flow level. The speeds indicate that platooning conditions are prevailing at this flow level. Graphs are drawn to show the speed-throughput and speed-density variation. These are presented in Figures 4.16 and 4.17 respectively. The results indicate how a mixed traffic behaves. The speed drop is exponential in unstable flow conditions as can be observed from Fig 4.17 The speed of the stream which consists of Maruti Cars and premiers, etc., reduces to about 22 Kmph which is close the average speed of a a freely moving tractor!. The results

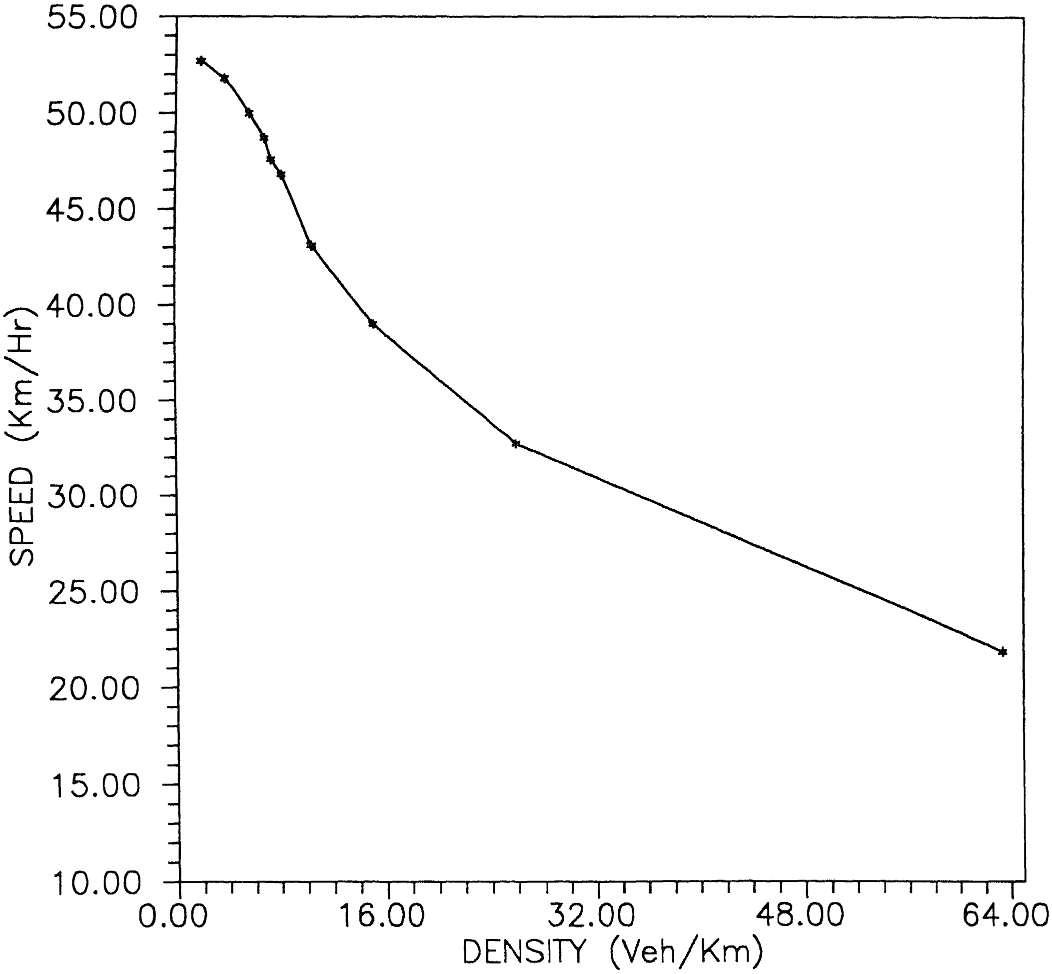


Fig 4.17 Speed-Density Variation for a Heterogeneous Traffic Stream.

indicate the effect of congestion that will be prevailing at these high flow levles and with a heterogeneous traffic stream like this.

CHAPTER 5

SUMMARY CONCLUSIONS AND SCOPE FOR FURTHER STUDY

5.1 Summary

The main objective of the present work is to determine the capacity and to evaluate level-of-service at various operating conditions on ideal, bidirectional single lane roads using the Indo Swedish Traffic Simulation Model.

A number of simulation experiments have been performed to achieve the above objective. To start with simulation runs were taken with only Maruti Car in the stream at various flow levels. The flow has been varied upto the anticipated capacity of the single lane road. The composition of the stream is then changed by introducing trucks into the stream. The percentage composition of the trucks is varied from 10 % to 100 %. The procedure is repeated with bus and tractor as the constituent vehicles in the all Maruti Car stream. To illustrate the effect of a heterogeneous traffic a traffic stream consisting of bus, truck, tractor, light commercial vehicle, jeep, premier, Maruti Car, ambassador is studied.

In all the simulation runs, at each flow level, the characteristics of the traffic stream like average speed, density, vehicle throughput, etc., are noted using the help of post processing programs.

The results are then used to analyze Passenger Car Equivalents and for capacity analysis.

First PCEs have been calculated for truck, bus and tractor. Two methods have been proposed for calculating the same. In the first method the number of cars displaced by the vehicle whose PCE value is under investigation is used for calculating the PCE values. This is achieved by equating the number of vehicles passed with only Maruti Car in the stream and with the vehicle plus Maruti Car in the stream. The PCE of a vehicle is then found out by dividing the difference in number of Maruti Cars passed by the number trucks passed.

In the second method the PCE of a vehicle is calculated by comparing the throughput of the streams with only Maruti and with Maruti plus the vehicle under investigation. The reduction in throughput contributed by the vehicle is used for calculating the PCE of that vehicle. The results from the second method are used for capacity analysis.

In the second stage the capacity of an ideal single lane road has been found out. The capacity is defined as the flow corresponding to the maximum throughput achievable. The level-of-service for these ideal conditions has also been determined using the speed-throughput-density results. The variation in level-of-service with each incremental addition of truck, bus and tractor has also been studied using the simulated results of the same. Speed and density have been used as criteria for defining level-of-service. The results give the idea as how the level-of-service varies with the addition of heavy vehicles like truck and slow moving vehicles like tractor. Finally the speed-density-throughput characteristics of a heterogeneous traffic stream are studied.

5.2 Conclusions

1. The results of PCE analysis indicate that there are different ways of looking at the concept of PCE and that different definitions can give widely different values for PCE of a vehicle. Hence care should be taken while devising the methodology itself. Since the objective of determining PCE 's is to express the characteristics of a heterogeneous stream into the characteristics of equivalent homogeneous stream, the method for calculating PCE should include all the relevant characteristics of the stream like speed, the number of crossing and passing maneuvers, etc.,

2. The results of PCE 's from the concept of number of cars displaced by a vehicle, suggest that the PCE of a vehicle decreases as its percentage composition in the stream increases. The results from the method of equivalent vehicle throughput suggest that PCE of a vehicle increases till certain composition of it in the stream, there after it decreases. This holds good for comparatively low flow levels. At high flow levels they decrease continuously. One would expect the second result to be more close to reality. As the proportion of a heavy vehicle increase in the traffic stream its effect increases upto certain point only. The results from the second method for truck and tractor show a striking resemblance with the results of the study on acceleration noise. The peak of the acceleration noise curve shifts from right to left in the same manner as the peak of the PCE value for truck and tractor using the second method. Hence the results from the second method are to be used for capacity analysis.

3. The capacity of a single lane road for ideal roadway, traffic and control conditions can be taken as 1070 Maruti Cars/Hour.

4. Speed is not an effective indicator of level-of-service when the traffic consists of only fast moving vehicles and when the road conditions are ideal. However it can be a good indicator of level-of-service when the traffic is heterogeneous as is indicated by the experiment on the heterogeneous traffic stream. For density the opposite holds true. Density is a better indicator of level-of-service when the traffic is homogeneous. When the traffic is heterogeneous the mere number of vehicles per unit space doesn't reflect the interactions that a heterogeneous traffic stream will be having. It seems that speed along with the number of interactions like crossing, passing, etc., of the traffic stream should be as an indicator of level-of-service when the traffic is heterogeneous. The fact that crossing and passing maneuvers involve greater degree of interaction and are very tedious, gives strength to this thought.

5. The results indicate that slow moving vehicles cause an exponential decline in the speed of the traffic stream and hence are more detrimental to the level-of-service than heavy motor vehicles.

6. The level-of-service drops drastically as the proportion of trucks or tractors increase in the traffic stream.

7. The results prove the versatility of the simulation model and indicate the advantages simulation can offer in understanding traffic behavior and for collecting data.

8. The results are to be viewed with caution as they could not be validated against field data.

5.3 Scope for Further Studies

There has been very little work has been done in this field of capacity analysis so far in India. Further work can be carried out in the following areas.

1. The capacity of a single lane road has been calculated for Ideal conditions. The adjustment factors needed for obtaining capacity at prevailing conditions can be studied. Adjustment factors can be calculated for

- Reduction in capacity due to reduction in shoulder width
- Reduction in capacity due to the presence of heavy and slow moving vehicles
- Reduction in capacity due to grades
- Reduction in capacity for non-ideal directional distribution (i.e. other than 50/50 distribution) of traffic etc.,

2. Similar studies can be conducted for analyzing capacity on two lane and Multi lane highways.

3. The variation of Passenger Car Equivalents for heavy vehicles on specified grades can be studied.

4. A beginning can be made for preparing Highway Capacity Manual for India after analyzing capacity on all the types of highway facilities. The Indo Swedish Traffic Simulation Model can be used as an efficient tool for such type of work as indicated by the present work.

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